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Feasibility study of a cruise ship for the Northwest Passage

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology

Turku 14.08.2017
Supervisor: Professor Pentti Kujala (Aalto University)
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Abstract of master's thesis

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Abstract

The cruise line industry is growing rapidly and new market opportunities are opening including the Polar areas. Global warming is enabling increasing shipping rates in the Arctic because sea ice is decaying in the Arctic Ocean. The Northwest Passage (NWP) is used as a shortcut between the northern Pacific and Atlantic regions. Diminishing sea ice has also opened market for cruise lining in the NWP and passenger rates in the area are increasing. The NWP offers an exotic alternative for Caribbean cruises, with pure, untouched nature, attractions and wildlife. Central location of the NWP, along the northern coast of North America and Canadian Arctic Archipelago is beneficial, since most of the cruise passengers are from US. Meyer Turku shipyard is well known to build biggest cruise ships in the world focusing on Caribbean market. However, the shipyard must be prepared to build all kinds of vessels and hence purpose of the thesis is to study feasibility of a cruise ship for the Northwest Passage (NWP). This is executed by converting the existing Turku shipyard ship to fulfil the requirements of Canadian authorities and the Polar Code to operate independently in demanding conditions of the NWP. Ice has significant effect on the ships safety, economy and comfort. The main goal of this thesis is to study operation conditions, select the suitable operation time window and design a ship concept feasible to operate in the selected season.

Literature related to ice conditions and shipping accidents in the NWP and ship design for the ice conditions were reviewed. In addition a support from Transport Canada were sought to help with legislation services. Also other operation conditions were studied, which have effect on the passenger comfort and ship's economy. Based on the ice conditions the ice breaking capability of the ship concept is selected and suitable design for the ship's hull and propulsion system are determined. Furthermore an adequate ice class is selected, which is the most important safety parameter. Sufficiency of the selected ice class was studied with POLARIS and AIRSS methods, which are risk assessment tools for ships operating in the Polar conditions. Calculations related to hull structures, weight and costs are performed to estimate the feasibility of the concept.

The business opportunities of the ship concept were studied by evaluating the ticket price based on investment and voyage costs. As the season in the NWP is discovered to be short due to lack of light and cold temperatures, other operational areas were studied and the Antarctic is found to be an appealing option for this kind of ship during offseason in the NWP. The ship was discovered to be economically feasible with reasonable ticket prices when operating summers in NWP and winters in Antarctic.

Keywords Northwest Passage, Polar code, cruise ship, feasibility study, ice class, Arctic

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Tiivistelmä

Risteilyliiketoiminta on ollut jo pitkään kasvusuhdanteessa, ja risteilyvarustamot ovat jatkuvasti kiinnostuneita laajentamaan liiketoimintaansa uusille markkinoille. Näihin markkinoihin kuuluvat myös Polaarialueet, ja ilmaston lämpenemisestä johtuva jäiden sulaminen onkin lisännyt Arktisen alueen laivaliikennettä. Arktisella alueella kulkeva Luoteisväylä on tunnettu meriväylä, jota käytetään oikoreittinä pohjoisen Tyynenmeren ja Atlantin välillä. Heikentyneet jääolosuhteet väylällä ovat avanneet uudenlaiset risteilymahdollisuudet alueella ja matkustajamäärät ovat kasvaneet. Risteily Luoteisväylällä tarjoaa eksoottisen vaihtoehdon Karibian risteilyille, sisältäen koskematonta luontoa, nähtävyyksiä ja villieläimiä. Lisäksi Luoteisväylän erinomainen sijainti pitkin Pohjois-Amerikan pohjoisrannikkoa ja Kanadan arktisia saaria on eduksi risteilyliiketoiminnalle, sillä yhdysvaltalaiset risteilevät eniten maailmassa. Meyer Turun telakka on tunnettu rakentamistaan maailman suurimmista risteilylaivoista, joiden operointi keskittyy Karibialle. Telakan täytyy olla valmis rakentamaan monenlaisia aluksia, ja tämän työn tarkoituksena onkin tutkia risteilyaluksen soveltuvuutta Luoteisväylälle.

Tämä tutkielma on tapaustutkimus, jossa tarkoituksena on suunnitella konsepti muuttamalla Turun telakan olemassa olevaa risteilylaivaa siten, että se täyttää viranomaisvaatimukset voidakseen operoida itsenäisesti Luoteisväylällä. Jääolosuhteilla on suuri vaikutus laivan suorituskykyyn, turvallisuuteen ja matkustajamukavuuteen. Tutkielmassa päätavoite on suunnitella laivakonsepti, jolla on mahdollista operoida Luoteisväylällä itsenäisesti risteilyille sopivana ajankohtana. Kirjallisuuskatsaus keskittyy jääolosuhteisiin ja onnettomuuksiin Luoteisväylällä, sekä laivan suunnitteluun jääolosuhteisiin. Lisäksi apua haettiin Kanadan liikenteestä vastaavalta Transport Canadalta, liittyen aluksen luokitukseen. Työssä tarkastellaan jääolosuhteiden lisäksi muita alueella vallitsevia olosuhteita, jotka vaikuttavat risteilyliiketoimintaan. Laivan jäänmurtokyky määriteltiin riittäväksi valittuna ajankohtana vallitsevien jääolosuhteiden perusteella, ja laivan runko sekä propulsio on suunniteltu täyttämään vaadittu jäänmurtokyky. Tärkeimpänä yksittäisenä turvallisuustekijänä valittiin aluksen jääluokka, jonka riittävyyttä tutkittiin POLARIS - ja AIRSS - riskienarviointojärjestelmillä. Konseptin soveltuvuutta tutkittiin laskemalla rungon rakenteita, painoa ja kustannuksia.

Työssä tutkittiin myös aluksen taloudellisuutta, perustuen polttoainekulutukseen ja investointikustannuksiin. Niiden avulla voitiin arvioida lippujen hintoja ja konseptin käyttöpotentiaalia. Koska Luoteisväylän operointikausi todettiin lyhyeksi kylmistä lämpötiloista ja valonpuutteesta johtuen, työssä tarkastellaan myös muiden alueiden käyttömahdollisuuksia. Lippujen hinnat arvioitiin olevan kohtuullisella tasolla, kun laiva pystyy operoimaan kesät Luoteisväylällä ja talvet Antarktiksella.

Avainsanat Luoteisväylä, polaarikoodi, risteilylaiva, soveltuvuustutkimus, Arktinen

Foreword

This Master's thesis was written for Meyer Turku shipyard during the academic year 2016-2017. I am greatly thankful for the Head of Sales & Design Olli Jantunen for letting me to select the topic based on my earlier experience and interest.

I would like to express my special thanks and appreciation to Professor Pentti Kujala, who provided very valuable suggestions, advices and feedback for me during the process. Special thanks also go to Mr. Kalle Honka for his helpful interview and thesis advisor Mikko Ilus.

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Valtteri Eronen

Table of the content

Acronyms and Abbreviations

ABS	American Bureau of Shipping (classification society)
AIRSS	Arctic Ice Regime Shipping System
AMSA	Arctic Marine Shipping Assessment
BP	Bollard Pull
CAA	Canadian Arctic Archipelago
CIS	Canadian Ice Service
CLIA	Cruise Lines International Association
CPP	Controllable Pitch Propeller
DNV GL	Classification society fused from DNV and GL
DAS	Double Acting Ship
FSICR	Finnish-Swedish Ice Class Rules
FYI	First Year Ice
FPP	Fixed Pitch Propeller
GHG	Green House Gas
IACS	International Association of Classification Societies
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MDLT	Mean Daily Low Temperature
MYI	Multiyear Ice
NWP	Northwest Passage
NSR	Northern Sea Route
BP	Bollard Pull
PC	Polar Class
POLARIS	Polar Operational Limit Assessment Risk Indexing System
PSC	Polar Ship Certificate
PSE	Personal Survival Equipment
PST	Polar Service Temperature
PWOM	Polar Water Operational Manual
RIO	Risk Index Outcome
RIV	Risk Index Value
SAR	Search and Rescue
SOLAS	International Convention for the Safety of Life at Sea
WMO	World Meteorological Organization
Z/DS	Zone/Date System

1 Introduction

1.1 Background and motivation

Over the past 10 years, the Canadian Arctic has experienced significant reduction in the sea ice cover, while the vessel traffic has more than doubled (See Figure1.). Ship passages throughout the Arctic is expected to continue to increase in the foreseeable future, motivated in part by predictions of ice-free summers in the Arctic Ocean as early as midcentury (The PEW Charitable Trusts, 2016). Some parts of the Arctic could see a doubling of current traffic levels by 2020 (Office of the Auditor General of Canada, 2014). Diminishing sea ice in Arctic sea enables the utilization of longer operation season for the two Arctic shipping routes, The Northwest Passage (NWP) and the Northern Sea Route (also known as the Northeast Passage). The Northwest Passage has been used in annual commercial shipping since the 1980s by tug/supply and tourism ships that have icebreaking capability or that are escorted by icebreakers (Government of Northwest Territories, 2015).

The Figure 1 illustrates that the commercial shipping in the NWP is increasing rapidly. However, there is no certainty of the future. The Canadian Ice Service (CIS) advices to consider future shipping possibilities in the NWP cautiously, since the predictions regarding ice-free Arctic may lead into over optimism. Variability of sea ice conditions is high and summers of occasional heavy ice conditions probably occur. Southern shift in pack ice and increase in drifting old ice can create choke points in narrow channels and navigation hazards limiting the usability of the NWP in the future shipping. (Government of Northwest Territories, 2015)

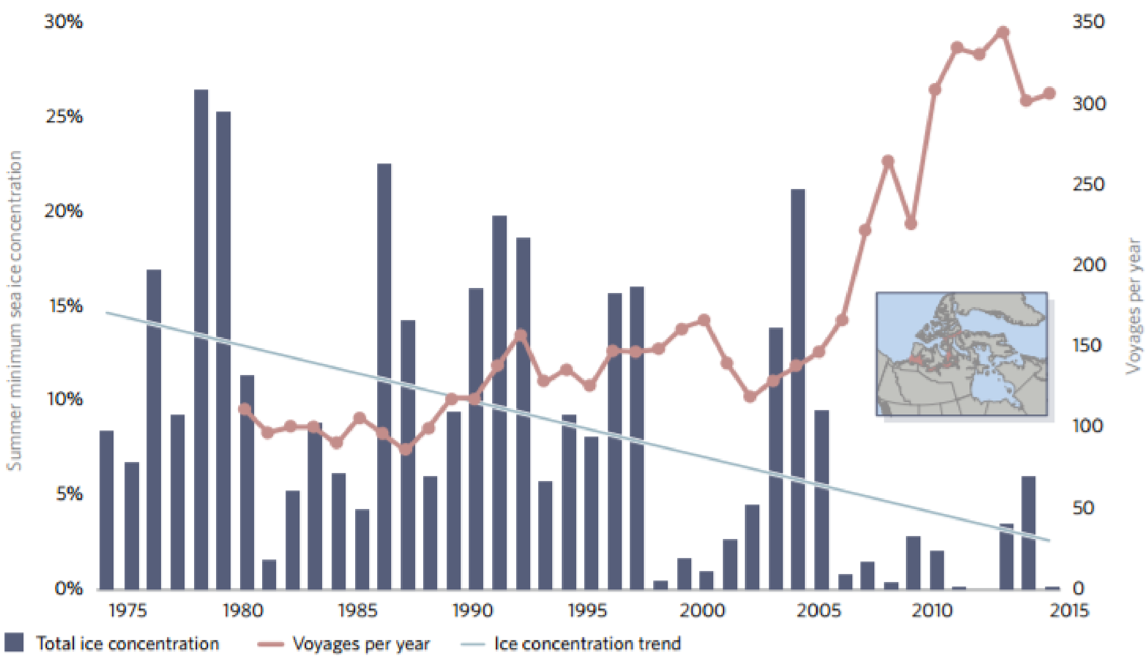


Figure 1. Ice concentration vs voyages (The PEW Charitable Trusts, 2016).

Estimating the expedition market potential is difficult, but even with a few percent share of the total steady growing cruise market the future the prospects would be bright.

The cruise industry's global economic input was about $40 billion in 2015 and it employed 448 vessels. US is the biggest single market with 11.28 million passengers of the total global 25.3 million passengers and the biggest share of cruise line regional deployment is Caribbean with 33.7% (CLIA, 2016). The all-seeing US passengers are seeking new experiences and Arctic gives tempting option to see fragile environment, exotic nature with Arctic local communities. However, the supply is outdated to meet the customer expectations and the fleet consists of smaller vessels measuring 5000 to 50000 gross tons with the average year of build of 1991. These smaller ships are much older on average than the largest cruise ships of 150 000 gross tons plus, which's average year of build was 2011. At the moment, expedition cruise operators charge very high per diems on voyages, for example, aboard Russian icebreakers or other vessels that are often neither new nor particularly luxurious. This will probably change as some expedition cruise operators clearly want to position themselves in the five-star market by introducing ships providing very high quality passenger accommodations. (Cruise Business Review, 2016) The Figure 2 presents the distribution of ships operating in the NWP.

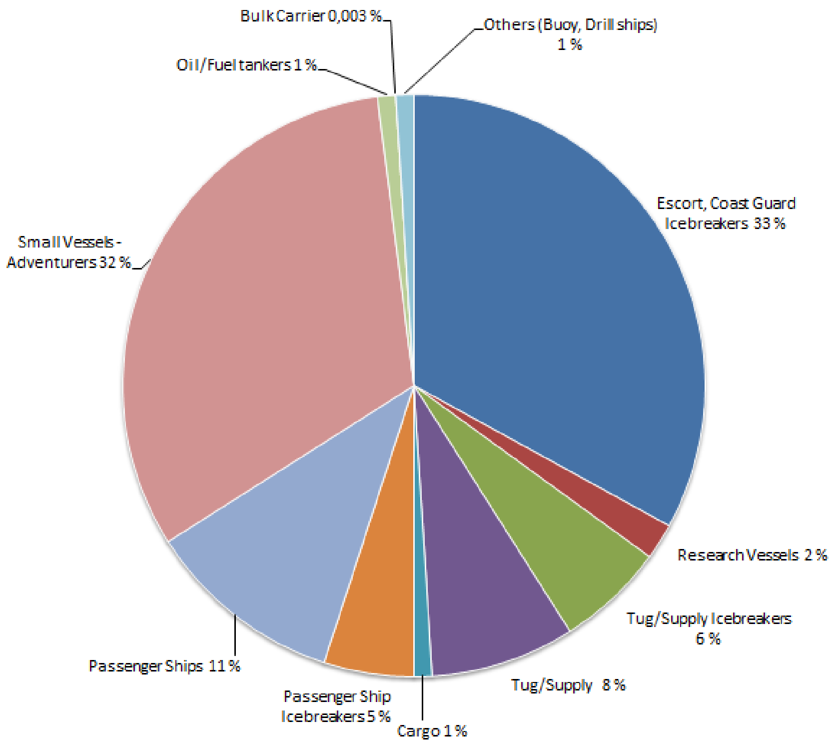


Figure 2. Distribution of ships in the NWP (Government of Northwest Territories, 2015).

There are number of unique demands required to be fulfilled, in order to operate in the Arctic region. First-year and multiyear is present in the Arctic causing additional loads on the hull, propulsion system and appendages. Sub-zero temperatures has impact on the ship, while cold and low light affect the crew. The Arctic environment is unique and fragile making it particular concern since ships have far more intimate and direct connection to it. Lack of infrastructure in Arctic regions is a huge challenge for passenger safety as well as oil spill since there is no equipment capable of cleaning the oil from ice infested waters. (ABS, 2009)

1.2 Scope and framework

The scope of this thesis is to study what technical requirements must be fulfilled and how it affects cruise ships cost structure when a hypothetical shipyard cruise ship is converted to ice strengthened Polar Class vessel. This paper's aim is to clarify the means for a Meyer Turku shipyard vessel intended to operate autonomously in the Northwest Passage to fulfil the requirements on studied ice and weather conditions. The applicability of different sources for operating conditions in the Northwest Passage is studied. In addition other potential operation areas are studied since the season in Arctic is limited to summer. Thesis' aim is to clarify the business opportunities for a cruise line owner in Northwest Passage; likewise educate the shipyard what technical aspects must be taken into account when building the case ship.

The thesis will concentrate upgrading existing Meyer Turku shipyard design to be compatible with the Polar Code requirements in the Northwest Passage. Fragile arctic environment is also considered by studying technical solutions to reduce human impact in the Arctic. This includes feasibility study of liquefied natural gas (LNG) as a power source. One important standpoint is to research how cruise ships effect on local Inuit and Inuvialuit way of life and possibilities to reduce drawbacks and increase positive impacts. Purpose of the thesis is to clarify what requirement must be fulfilled in a concept level and estimate the added costs to converse typical shipyard cruise ship to be Northwest Passage operation ready. This thesis will increase understanding the market potential in Northwest Passage for a large scale product which is common for Meyer Turku.

The purpose of this paper is to take deeper insight into technical requirements which needs to be fulfilled in order to have safe and efficient autonomous operation in the NWP. A determination of operation profile will be conducted in order to clarify the ice conditions. Also, open water operations must be considered to keep the operating costs down. Therefore, the design process includes balancing between the open water performance and good icebreaking characteristics. IACS Polar Classes will be examined and the most suitable one will be chosen for case ship to meet the operational conditions requirements in selected time-windows and areas. Polar Class refers to ice class system implemented by the *IACS in Unified Requirements for Polar Ships (2006)* which provides a standardized ice classification for ships. By applying the selected Polar Class, the case ship structural and machinery are determined to meet the class requirements and the effects on weight and costs are also estimated. In the thesis a comprehensive risk analysis of the case ship operation in Northwest Passage is not carried out, but safety related issues and risks are emphasized with possible solutions.

1.2.1 Research methods

A qualitative approach is selected, since no single and exact method for any aspect of cruise ship design for ice exist. A literature review and existing studies are applied in various depths a multitude of methods found – and the concept design is then a synthesis of results from different sources deemed most appropriate.

In order to successfully make the concept, the ice and temperature conditions are studied in Northwest Passage. The Northwest Passage selection is based on the existing cruise ship and future trends of cruise business. A study is carried out in order to determine the availability of online ice charting and weather data. In addition, to understand the challenges related to the route, an interview is carried out with chief officer Kalle Honka, who has participated in sailing through Northwest Passage with Finnish icebreaker MSV Fennica. Support is also sought from Transport Canada with email to help with the regulatory related issues. Advice regarding requirements for independent operation in the NWP is requested from Transport Canada which is responsible for the regulations in the Canadian Arctic. To back up the selected ice class an evaluation with Polar Operational Limit Assessment Risk Indexing System (POLARIS) is executed with worst case scenarios in selected time window and areas.

Once the concept is ready, including knowledge of technical specification, economic study is formulated. Collecting cost information from manufacturers is required in order to formulate the economic analysis. Safety aspect is the most important factor when designing a ship and it is vital to analyze risks for this kind of operation. However, accident data is limited because the operations in the area are limited and generally the vessels navigating there have limited number of passengers. For the above reasons the risk analysis stays in speculative level.

1.2.2 Theoretical background and literature

There is no direct guidance or literature on how to design a cruise ship in the Arctic environment. There are so many variables involved in the process which must be taken into account. Design of ice breaking ships by Riska, 2010 provides basic understanding for designer how the ice is acting on a ship. Literature related to the ice conditions in the Northwest Passage is easy to find which is essential for determining adequate ice class. Due to easy access with satellite images, the studies related to ice conditions mostly focuses on the sea ice extent. One of the few articles regarding ice thickness is Haas & Howell, 2015 Ice thickness in the Northwest Passage. Also Canadian Ice Service (CIS) provides lots of information of ice conditions in the area. IACS, 2011 requirements concerning polar class gives unequivocal requirements for the selected Polar Class. Transport Canada offers guidelines and legislation for passenger vessel operating in Canadian Arctic Waters. Most importantly the International Maritime Organizations (IMO) code for ships operating in polar waters (Polar Code) offers guidance and regulations related to design, construction, operational, equipment, search and rescue (SAR), training and environmental protection guidelines to ships planning to operate the polar waters. Ihalainen, 2017, studies in his thesis how to apply Polar Code requirements in general for cruise ships including possible solutions for safety aspects.

Polar Code offers risk management tool The Polar Operational Limit Assessment Risk Indexing System (POLARIS), which can be used as aid when choosing the Polar Class or when planning the route. Arctic Ice Regime Shipping System (AIRSS) is a similar risk management tool than POLARIS, meant for ships operating in the Canadian Arctic waters. The thesis studies both POLARIS and AIRSS in legislation purposes for ice class validation. The study of TraFi & Kamarainen, 2015 has studied applicability of POLARIS by collecting full scale data on ice conditions and ice induced loads onboard S.A Agulhas II in the Antarctic. This data can be used in the thesis when selecting the Polar Class and also usability of the concept in the Antarctic.

2 The Northwest Passage

The NWP is a connection between Baffin Bay and Beaufort Sea located in the Canadian Arctic Archipelago (CAA), which consist of channels, sounds straits and gulfs. The importance of the NWP lies in the fact that it can be used as a shortcut between northern Pacific and Atlantic regions reducing the shipping distances and the need of Panama and Suez canals. The NWP has an alternative route along the coast of Siberia called the Northern Sea Route (NSR). (Haas & Howell, 2015) Infrastructure in the CAA is very underdeveloped and the availability of ice breaking services is limited. Canada offers its limited icebreaking services free of charge with two heavy icebreakers resulting in long response times. Ice and navigation conditions are much more challenging in the NWP compared to the NSR. (Stephens, 2016) This can be perceived from the Figure 3 where the NWP and NSR are represented with ice concentration in September 2016.

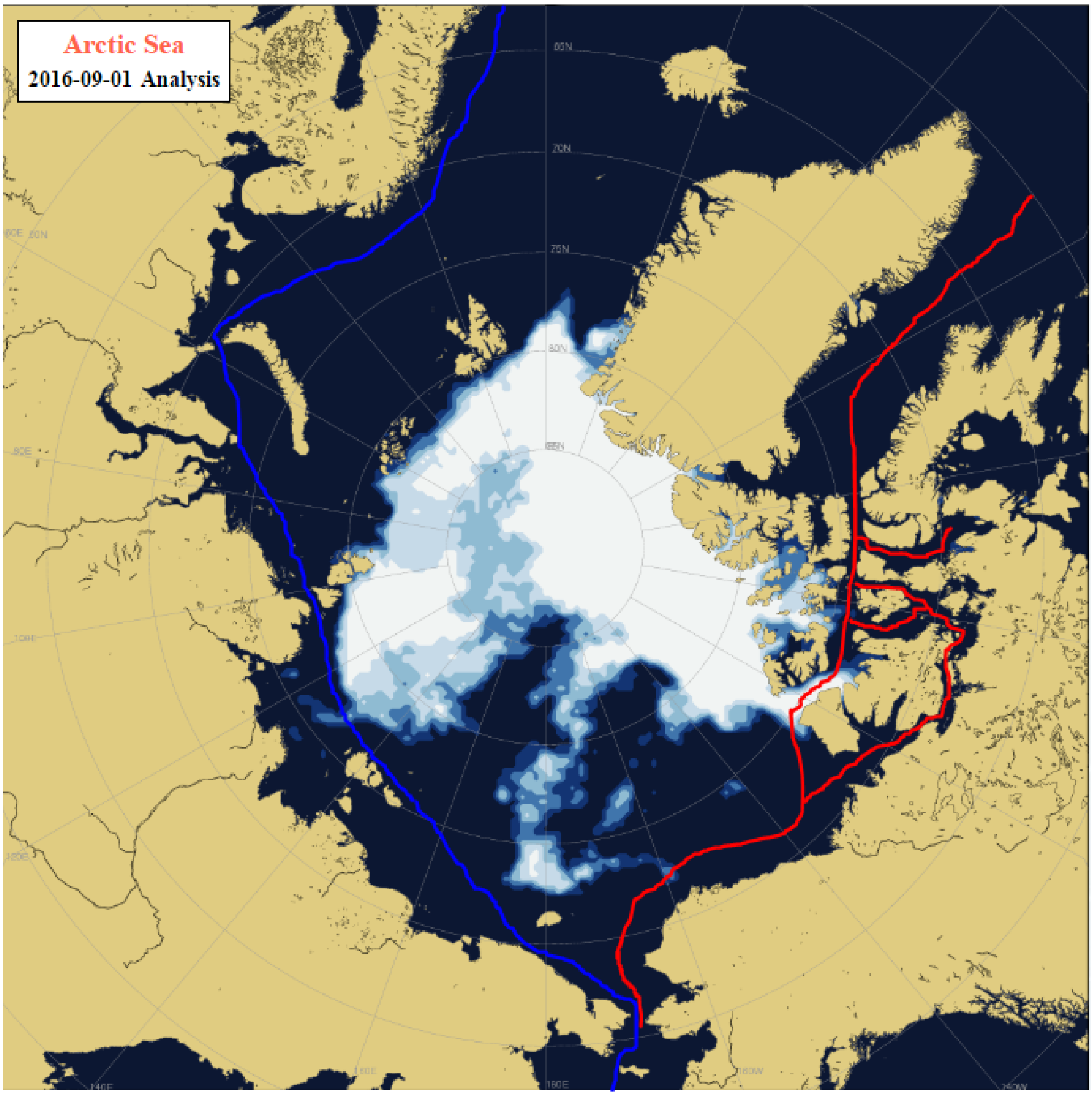


Figure 3. NWP marked with red color and NSR with blue.

2.1 History and Inuit/Inuvialuit cultures

A short route connecting the Atlantic and Pacific Oceans has significant economic value and it was appreciated early. Europeans started to explore the route as early as 1500s with no luck. Explorations continued through next centuries without success. In the 1849 Robert McClure and crew were first to survive a trip through the Northwest Passage, however, they were rescued by a sledge party after spending three winters on ice suffering dying of starvation. Norwegian explorer Roald Amundsen was the first who was able to navigate through the NWP in 1903-1906. Later in 1940-1942 Henry Larsen was able to navigate from West to East and in 1944 East to West first time in a single season. The operation season is generally from late July to mid-October – depending on the route and year. (Arctic Council, 2009)

Increasing cruise lining in the area has many concerns to local cultures which inhabit the area. Those cultures are traditional with old fashioned manners and are relying on primary production like hunting sea mammals and handcrafting. Researchers confirm that increasing maritime traffic in the Northwest Passage produces noise that can drive sea mammals away. Prices in local grocery stores are very high and locals want to be materially independent. If hunters have to go out further and longer to search for sea mammals there is more expenses like fuel costs and they are away from their family longer. Hunters pay an important role for the community because they share all their cash to whole community. It goes beyond of just nourishment; seals are the heart of their culture. (Duhaime-Ross, 2016)

2.2 Cruise line market potential

Voyage through majestic waterways, spectacular glaciers and towering fjords with wild nature seems to appeal wealthy customers. Market potential for cruise line operations in the NWP is difficult to estimate but in 2016 Crystal Serenity's successful voyage supports the demand of a larger scale cruise ship operations in the area. The whole voyage from Anchorage to New York took 32 days covering 7297 nautical miles. It is remarkable milestone since Crystal Serenity is the first passenger ship to navigate over the top of North America through the Arctic waters. She was escorted by research vessel Ernest Shackleton appointed with the DNV ICE-05 ice-class notation. Her purpose was to support Crystal Serenity with ice breaking capabilities, two helicopters for special adventures, expert expedition crew and responses for emergency situations. (Riviera Maritime Media, 2017)

The NWP offers special opportunity to see sea and land mammals like polar bears, grizzly bears, musk oxen, narwhals, beluga whales and walrus (Historica Canada, 2016). There is also historical appeal on the route which can evoke interest for some passengers. Pristine wilderness and melting glacier offer something unique and different, when comparing to crowded islands of Caribbean.

Berths on the Crystal Serenity for the Northwest Passage cruise was around $20,000 per person and running up to $120,000 for a deluxe stateroom (*Crystal Cruises*, 2017). The Table 1 presents the general characteristics of Crystal serenity and the Figure 4 represents the journey.

Table 1. Main characteristics of Crystal Serenity

Type	Cruise Ship
Tonnage	68,870 GT
Length	249,94 m
Beam	32,31 m
Draught	7,62 m
Propulsion	2 x ABB Azipod
Capacity	1,070 passengers
Crew	655
Ice class	Finnish-Swedish ice class 1C

Figure 4. Crystal Serenitys's journey in 2016 (Humpert, 2016).

2.3 Interview with the 2nd Officer of multipurpose icebreaker Fennica

An e-mail conversation was carried out in order to have more practical aspect of challenges operating throughout Northwest Passage. Interviewee Kalle Honka was the 2nd officer of multipurpose icebreaker Fennica when she navigated throughout NWP in 2015.

Table 2. Information about the route of icebreaker Fennica.

Dutch Harbor – Nuuk 16.10 – 31.10.2015	15 days
Distance Dutch Harbor – Nuuk	4000 miles
USA/Canada Border - Nuuk	8 days

Questions were related about operation of the ship, operational conditions, ice conditions and risks. According to Kalle Honka (Personal communication, February 27.2017) the ice conditions changed repeatedly in the end of October. Moving from the United

States the ice was mainly new ice and pancake ice. Also in the Amundsen Gulf the ice conditions were easy: new ice and level ice (5-20cm). Harshest ice conditions were encountered between leg in Cambridge Bay and King William Island. In the time there was one and second year ice present. There would not have been way through with ordinary vessel. From that moment on the ice conditions were eased up with new level ice and in some parts multiyear ice. Halfway from Devon Island to Baffin Bay the ice field ended. In the Baffin Bay the icebergs were the biggest issue. Honka also mentioned that the ship must have good communication systems and in the area the infrastructure and search and rescue services are primitive.

2.4 Ice conditions

Studies related to ice conditions in the NWP mostly focuses on ice extent or area (*Figure 5),* because it is easy to do with satellites, nevertheless the actual volume of ice is as important, if not more so. Ice volume is a combination of extent and thickness. New findings from on-site research have found that ice in the NWP can still be too thick and ice conditions far too unreliable in summer for it to become a regular shipping route. (Montgomery, 2015)

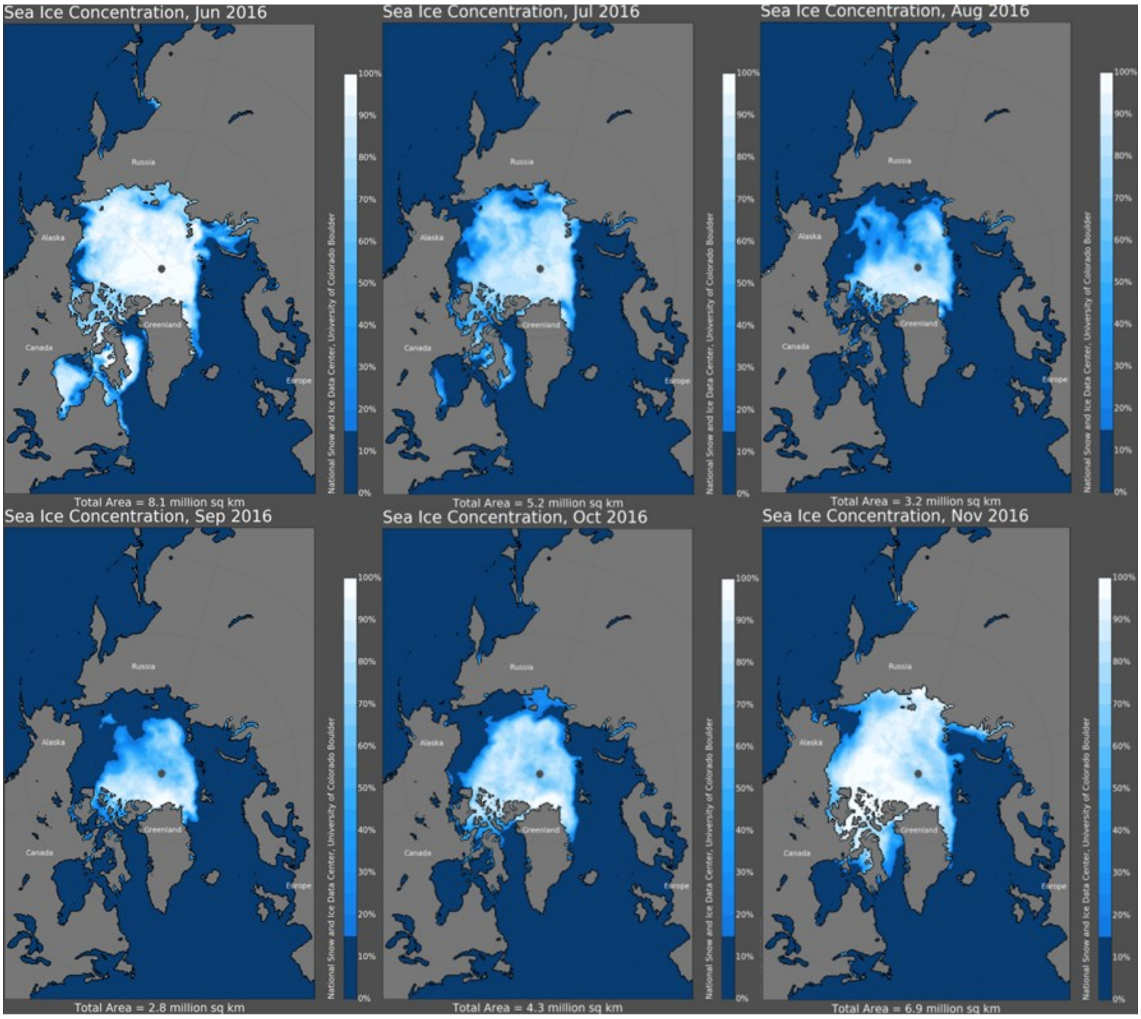


Figure 5. Ice concentration on the Arctic Sea on June until November 2016 (NSIDC, 2017).

The Figure 5 shows that the sea ice extent is diminishing from June to September. It also shows that the Northwest Passage is almost ice free in August and September.

Even though the ice free season is increasing through the passage, there is a danger of over estimating future shipping possibilities in the NWP. Ice behavior in Narrow Channels of Canadian Arctic Archipelago is hard to estimate and multiyear ice (MYI) conditions can actually increase. MYI can originate in the NWP by two ways: locally or imported. Some first year ice can survive through the summer formulating local MYI conditions, although most of the first year ice (FYI) melts. Imported MYI can occur when the melting Arctic Ocean releases mobile MYI advection through the Queen Elizabeth Islands (QEI) to the NWP. These imported MYI can actually increase, due to continuously warming climate, melting in the Arctic ocean can cause more ice drift in to the passage (Montgomery, 2015). MYI is the largest hazard for ships because it is known to be thickest sea ice in the world and it has really high mechanical strength. (Haas & Howell, 2015)

In May 2011 and April 2015 a research team measured ice thickness in the NWP using a helicopter and airplane with electromagnetic induction sounding. Even though these measurements were outside the shipping season, the ice conditions measured can be used to predict the forthcoming summer seasons ice conditions. The research team found out that ice in the most regions is just less than 2 meters thick but there were many areas were the thickness was between 2-3 meters (see Figure 6). (Haas & Howell, 2015)

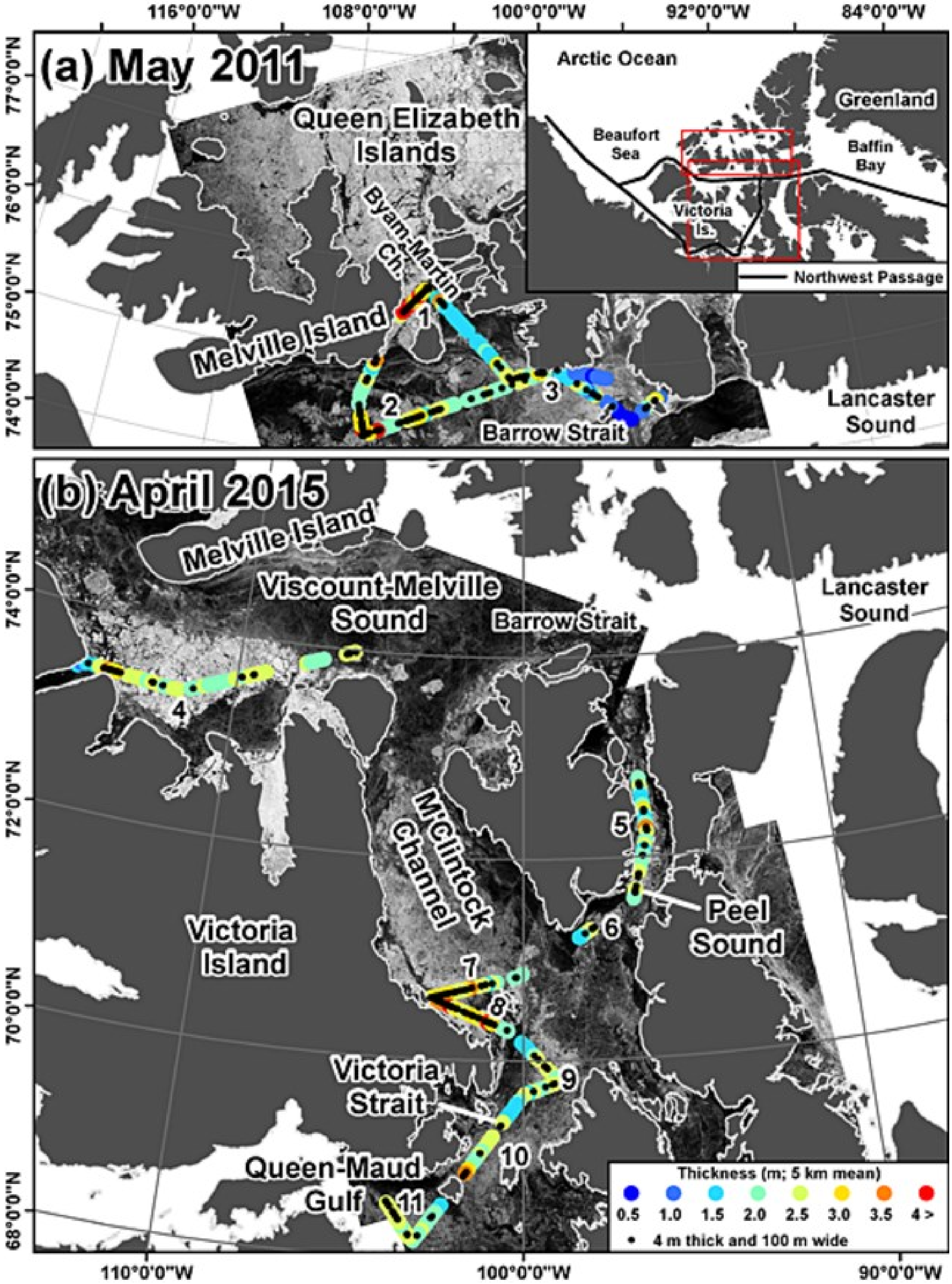


Figure 6. Maps of the Canadian Arctic Archipelago with tracks of ice thickness surveys (Haas & Howell, 2015).

In the Figure 6 individual black dots mark the locations of individual thick ice features with thickness over 4 m and width more than 100 m. When considering the MS Serenity's route in the NWP the thickness measurements which are located near to the route are 5, 6, 9 and 10.

Table 3. Ice Thickness Statistics for All Regions Surveyed in 2011 and 2015 (Haas & Howell, 2015).

Year	Profile (length, km)	Ice Type	Mean (stdev) (m)
May 2011	1 (37)	MYI	3.84 (2.04)
	2 (127)	MYI	3.21 (1.77)
	3 (242)	FYI	2.00 (1.18)
April 2015	4 (245)	SYI	2.61 (0.81)
	5 (131)	MYI	2.47 (1.04)
	6 (37)	FYI	2.33 (0.87)
	7 (110)	MYI	2.78 (1.09)
	8 (45)	MYI	3.21 (1.15)
	9 (95)	MYI	2.51 (0.77)
	10 (106)	FYI	2.51 (1.00)
	11 (124)	MYI	2.48 (0.70)

The Table 3 shows that there are FYI and MYI ice conditions with mean thickness approximately around 2.5 meters in April 2015 in the Crystal Serenity's route.

2.4.1 Canadian Ice Service (CIS)

"The Canadian Ice Service's mission is to provide the most timely and accurate information about ice in Canada's navigable waters." (CIS, 2017) The covered areas in the service include Labrador Sea, Hudson Bay, Baffin Bay, Bering Strait, Chukchi Sea, Beaufort Sea and the Great Lakes. The Figure 7 presents the service areas by the CIS excluding the Chukchi Sea and Bering Strait. The CIS provides the daily regional ice charts, departure from normal concentration charts and iceberg charts. In addition to these, service provides separate satellite image analysis charts and aircraft observation charts. An estimate of the total situation is made by integrating data from satellite images with ship and aircraft-based visual observations. The charts describe ice concentrations in tenths (as required by the POLARIS in voyage planning), ice types or stage development and the form of the ice. The relevant boundary lines for different ice conditions which are essential for navigation of the ship in ice are determined by the standards.

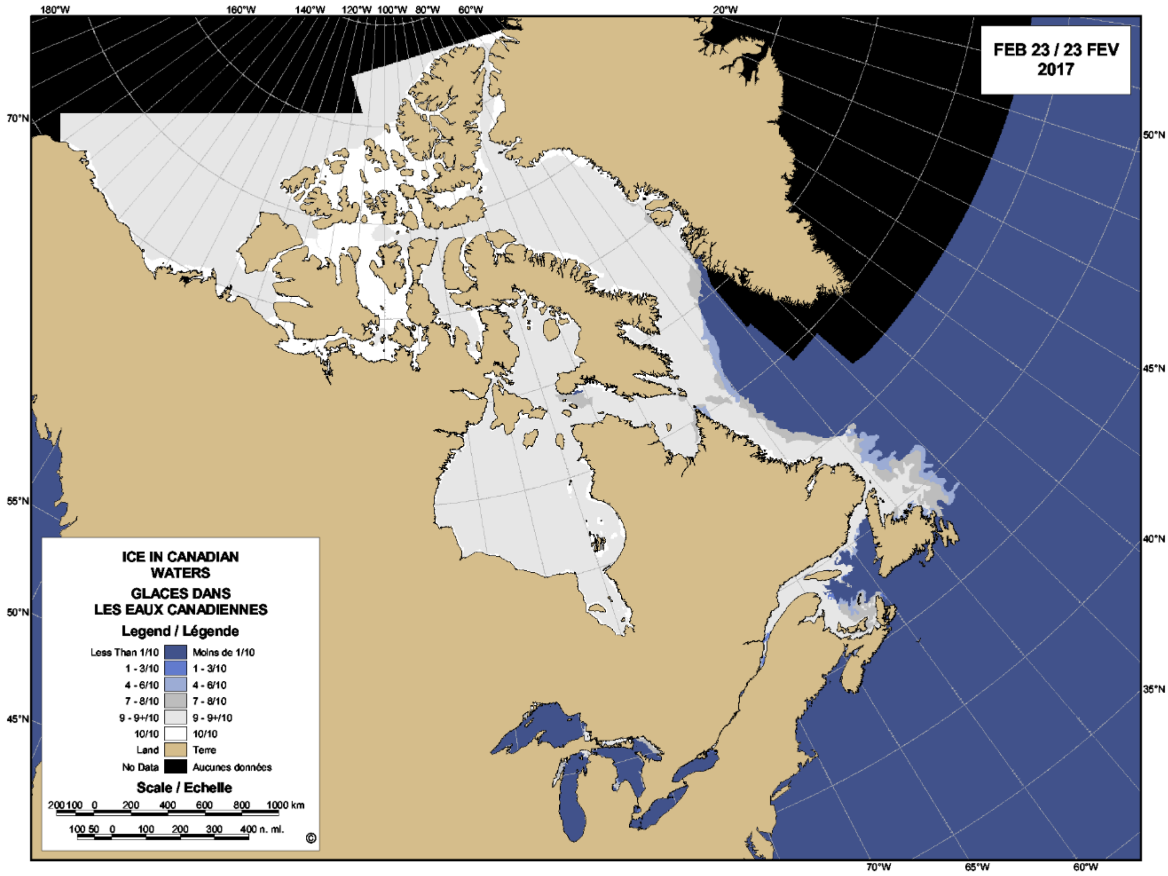


Figure 7. Example ice map provided by CIS from 2.3.2017 (CIS, 2017).

Ice regime rarely consists of a single ice type and continuous coverage, but is a combination of several thicknesses and floes of different ice types. The cover itself is rarely uniform but rather a combination of different sized floes that are separated with open water or extremely thin layers of ice. The world meteorological organization (WMO) Egg Code (see Figure 8) characterizes ice based on ice type (stage of ice development, see Table 4) and floe size (see Table 5) displaying these characteristics for each ice regime on an ice chart by dividing the total concentration into partial concentrations. Thus, the actual characteristics of an ice regime may be described by a series of partial concentrations, each with an associated ice type and floe size.

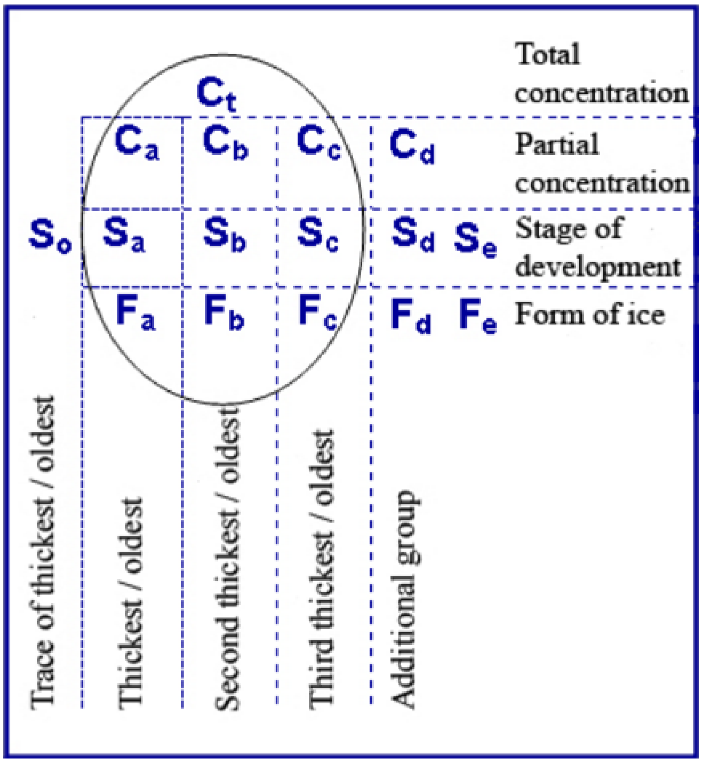


Figure 8. Diagram of the Egg Code (CIS, 2017).

Table 4. Stage of development and thickness (S_o S_a S_b S_c S_d S_e) (WMO, 2014).

Stage of Development for Sea Ice	Thickness	Symbol
New Ice	< 10 cm	1
Nilas, Ice Rind	< 10 cm	2
Young	10 – 30 cm	3
Gray	10 – 15 cm	4
Gray – White	15– 30 cm	5
First - Year	>= 30 cm	6
Thin First - Year	30 – 70 cm	7
Thin First - Year – First Stage	30 – 70 cm	8
Thin First - Year – Second Stage	50 – 70 cm	9
Medium First - Year	70 – 120 cm	1.
Thick First - Year	> 120 cm	4.
Old –Survived at least one season’s melt	> 200 cm	7.
Second-Year	> 200 cm	8.
Multi-Year	> 200 cm	9.

Table 5. Forms of Sea Ice (Fa Fb Fc Fp Fe) (WMO, 2014).

Forms of Sea Ice	Floe Size	Symbol
New Ice	0-10 cm	X
Pancake Ice	30 cm – 3 m	0
Brash Ice	< 2m	1
Ice Cake	2 – 20 m	2
Small Ice Floe	20 – 100 m	3
Medium Ice Floe	100 – 500 m	4
Big Ice Floe	500 m – 2 km	5
Vast Ice Floe	2 – 10 km	6
Giant Ice Floe	< 10 km	7
Fast Ice		8
Ice of Land Origin		9
Undetermined or Unknown (Iceberg, Growlers, Bergy Bits)		x

2.4.2 Original Ice Thickness Program

In the 1947 CIS started to measure ice thickness and snow depth measurements from 195 different sites such as Cambridge Bay and Resolute. This was called Original Ice Thickness Program. Most of these sites had stopped taking measurements by the end of 2001. However, climate change evoked interest to update this historical dataset and the program was relaunched in the fall of 2002 with limited number of stations in the Canadian Arctic. Based on these measurements, three different ice conditions (mild, severe, average) in Cambridge Bay are represented in the Figure 9 and in Resolute in the Figure 10. Thickness data was not available between July to end of November. These figures shows that the average, severe and mild ice conditions are timed in different year in Cambridge Bay and Resolute for example in 2008 are average ice conditions in Cambridge bay but heaviest conditions in Resolute. (CIS, 2017)

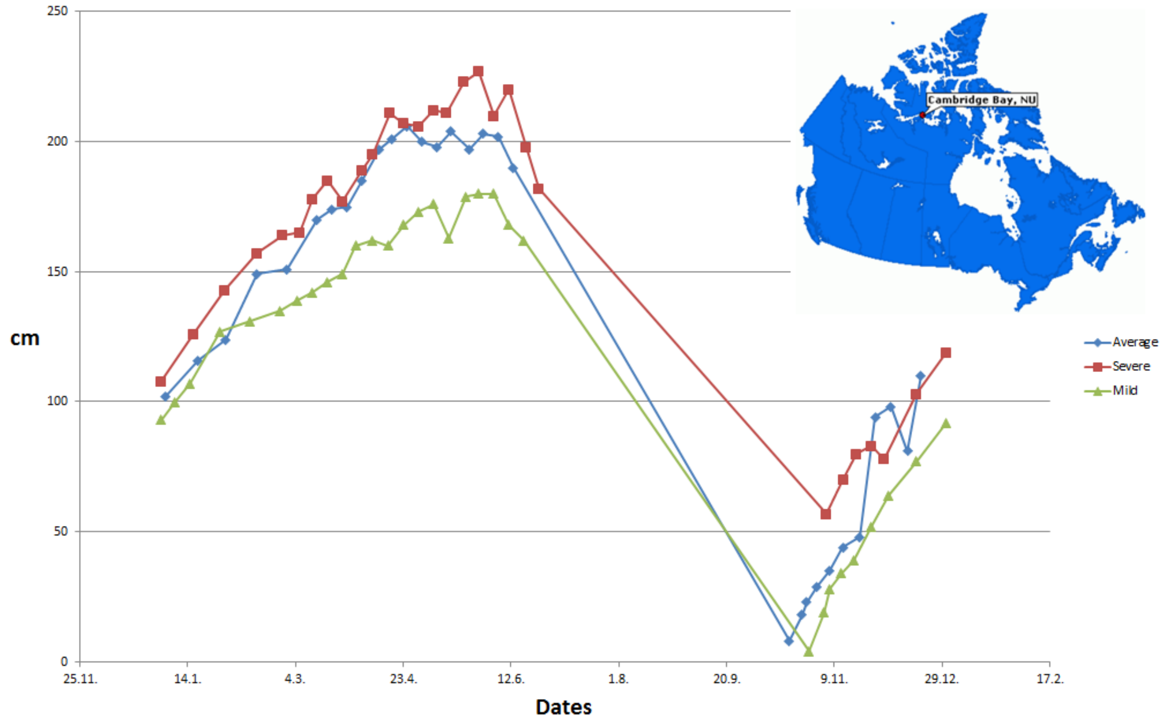


Figure 9. Ice thickness in Cambridge Bay in years 2004 (severe), 2008 (average) and 2010 (mild).

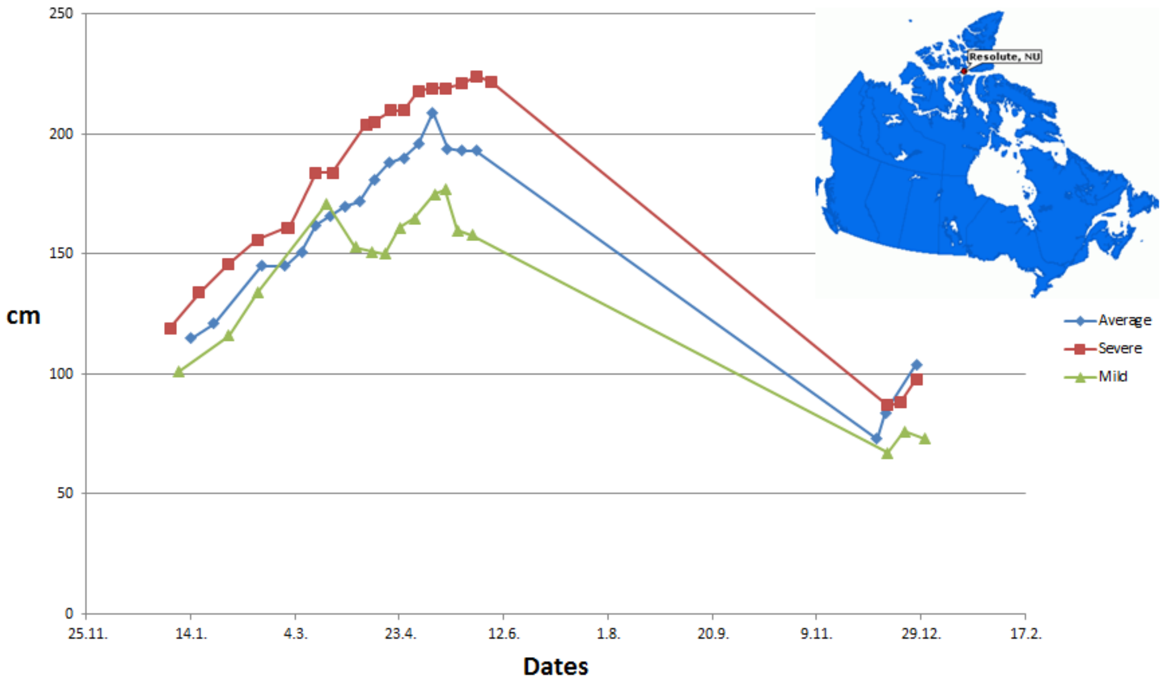


Figure 10. Ice thickness in Resolute in years 2003 (average), 2008 (severe) and 2010 (mild).

Since there were no sea ice thickness data available from July to September the sea ice extent is studied in the areas in the August in the years 2004, 2008 and 2010 to see how it complies with ice thickness results. The Figure 11 represents the sea ice extent.

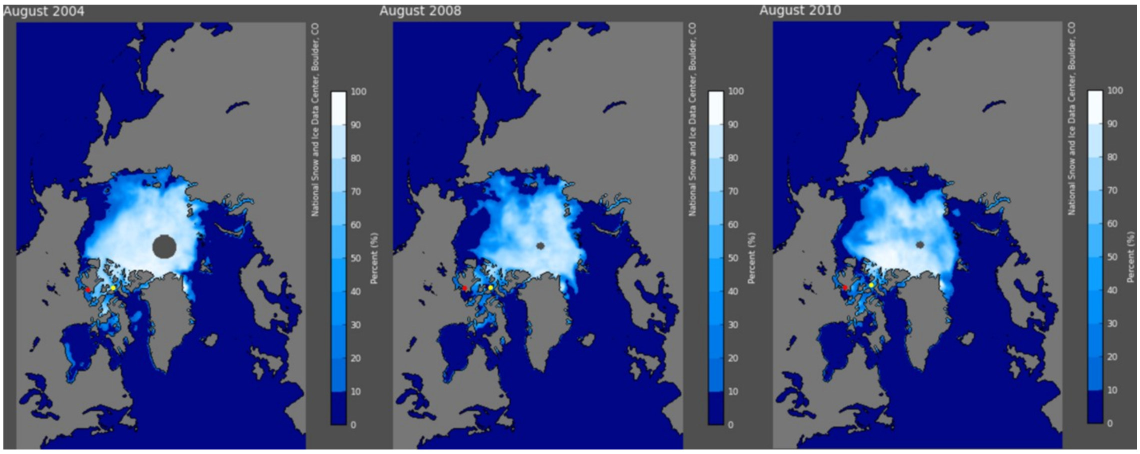


Figure 11. Sea ice concentration in August 2004, 2008 and 2010 with locations of Cambridge Bay (red) and Resolute (yellow) (NSIDC, 2017).

Weather conditions in the summer especially in June and July determine large extent how the ice cover is going to act. The ice loss can be rapid if there are right atmospheric conditions during those two months, but if the conditions are less favorable for ice melt the ice conditions can be challenging. Because forecasting summer weather in advance is impossible, predicting the upcoming ice conditions in the late summer is limited. (Vinas & Ramsayer, 2016)

2.5 Other Environmental Factors

Not only the ice conditions form a hazard to a ships operating in the NWP, even if relatively ice-free conditions are considered like in the mid-August 2016 (see Figure 5) there are other environmental factors in the area which must be taken into account for safe operations. The NWP and Beaufort Sea are challenging for seafarers due to shifting sand-gravel bars, fog, unmarked shallow areas and unpredictable weather. Increasing shipping rates in the area would set off a need for high preparedness for environmental incidents. The Figure 12 shows the route of Crystal Serenity included with water depths in CAA. The depth on the route ranges from 20 meters and demand for Crystal Serenity for safe operation is 10 meters with a draft of 8 meters. (Humpert, 2016)

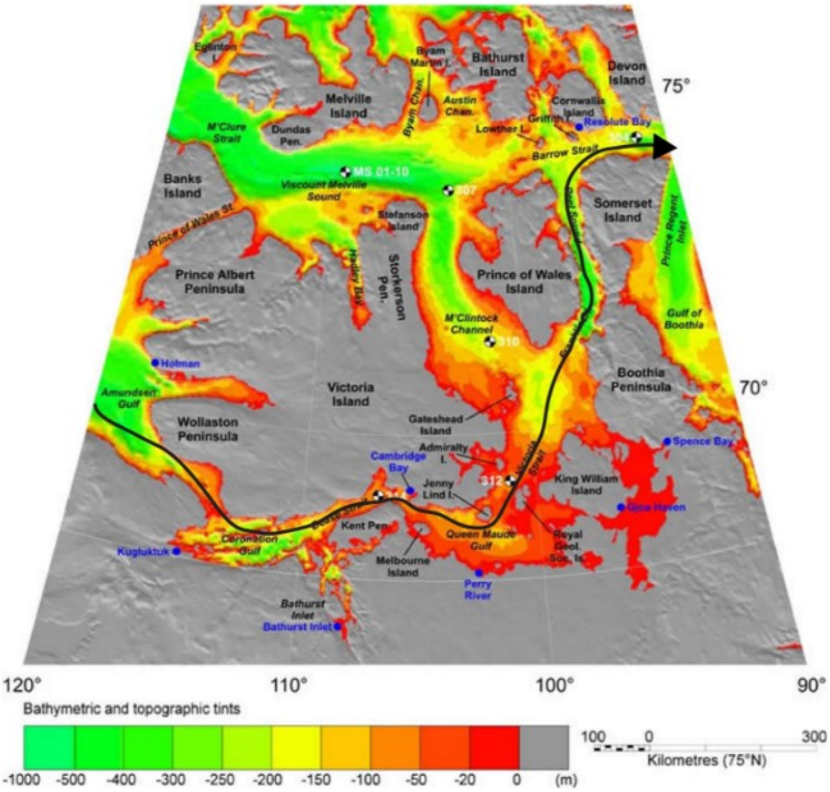


Figure 12. Crystal Serenity's route in CAA with water depths (Humpert, 2016).

2.5.1 Daylight

When it comes to the customer experience visibility and daylight plays an important role. Winter months are dark and there are days without sunrise – Polar nights. On the contrary in the summer season there is phenomenon present called midnight sun, when the sun remains visible at the local midnight. Cambridge Bay is located in a central location of the NWP and the 24 hours of sunshine is from May 20 to July 23 and darkness from November 30 to January 11. The limits of midnight sun and polar night extend approximately 50 nautical miles north and south of the Arctic Circle. (MSC, 2001) In order to have enough sunlight for passengers to enjoy the views and activities during the days the daily sunrise and sunset times are studied. At the end of October (31.10.2016) the sunrise was at 9.19 and sunset 16.05 which gives 6 hours and 46 minutes of daylight. This is used as boundary of the concept cruise ship operation period since it is not customer friendly to operate in the dark. The start of the operation period however is not determined by the daylight since at the end of May the sun is up all day until end of June. The limiting factor for start of the cruise season is the ice conditions. The Figure 13 presents the daylight distribution thorough the year.

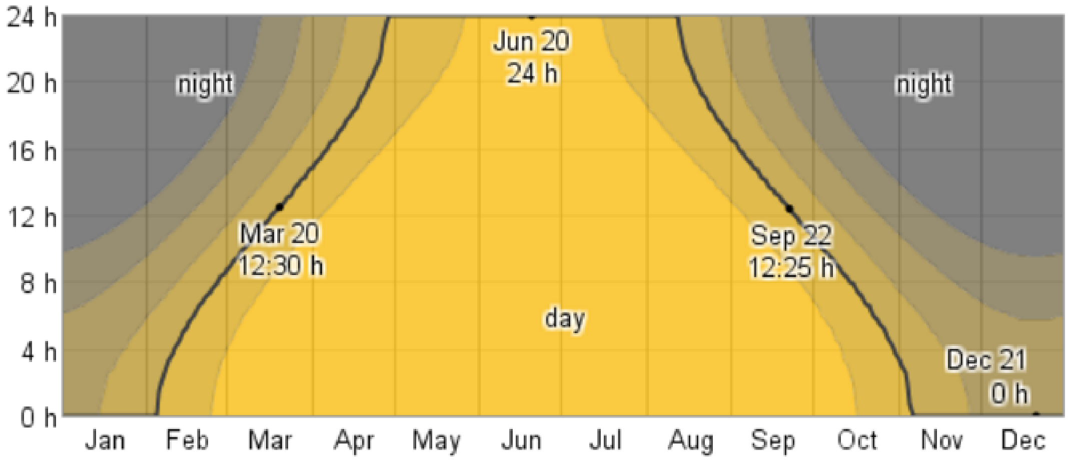


Figure 13. Annual daylight distribution in Cambridge Bay (Time and Date, 2016).

2.5.2 Temperatures

Operation temperature is an important factor when considering passenger comfort and safety related issues. When considering temperatures below zero: the effect is not limited only for the ice coverage, but also in function of the equipment and systems. It is determined in Polar Code's Polar Water Operational Manual (PWOM) that the ships equipment and survival systems shall be fully operational in Polar Service Temperature (PST) during the maximum expected rescue time. The PST is defined that it shall be set at least 10°C below the lowest mean daily low temperature (MDLT) for the intended operational window and geographical location. Mean daily low temperature is defined that the "mean value of daily low temperature for each day of the year over a minimum 10 year period". Ships operating in areas where the lowest MDLT remains above the -10 °C, the PST definition is not required. (IMO, 2015) The Table 6 shows that MDLT is in October is -16.4 °C, meaning that the PST is -26,4 °C. It would be wise for to choose the operation window for the concept, so that the MDLT remains above -10 °C. With this way the ship could avoid extra costs related to PST operations.

Table 6. Temperature data for Resolute Bay Airport, normals, extremes 1947-present (Environment Canada, 2017).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Now	Dec	Year
Record high °C	-0.8	-3.9	-2.7	0.0	6.1	18.3	20.1	15.3	9.4	2.0	-2.8	-3.6	20.1
Average high °C	-28.6	-29.0	-26.8	-18.3	-7.4	2.6	7.3	4.2	-2.0	-10.5	-19.5	-24.5	-12.7
Daily mean °C	-32.0	-32.4	-30.2	-21.8	-10.3	0.4	4.5	2.0	-4.1	-13.4	-22.7	-27.9	-15.7
Average low °C	-35.3	-35.8	-33.6	-25.3	-13.3	-1.9	1.7	-0.3	-6.1	-16.4	-25.9	-31.3	-18.6
Record low °C	-52.2	-52.0	-51.7	-42.1	-29.4	-16.7	-3.1	-9.3	-20.6	-37.3	-42.8	-46.1	-52.2

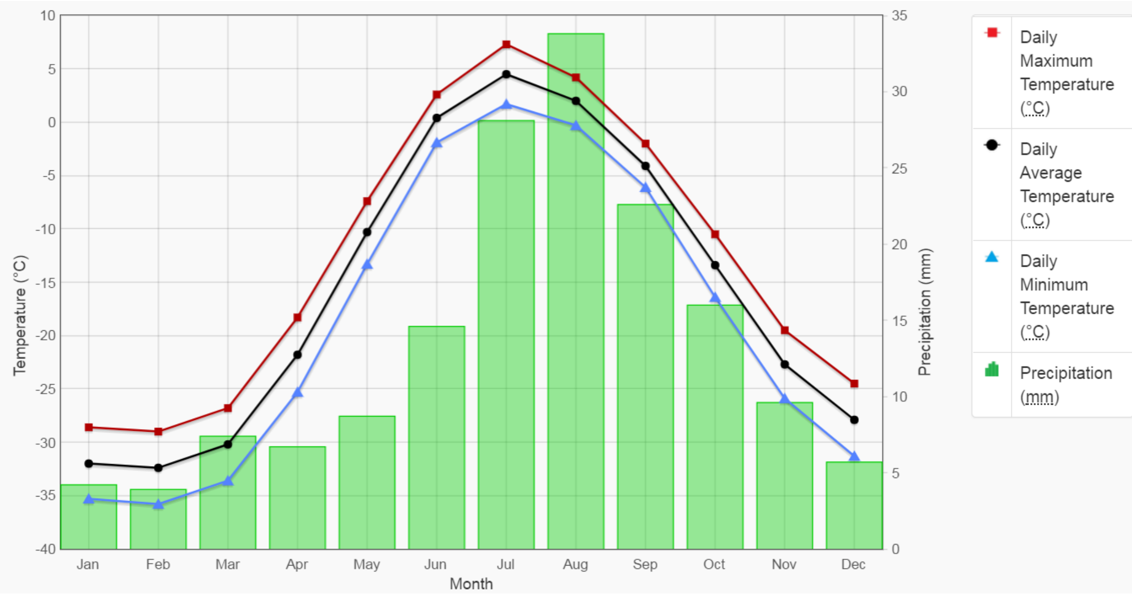


Figure 14. Temperature graph for Resolute from 1981 to 2010.(Environment Canada, 2017).

The Figure 14 shows that the operations should stop around in the mid-September in order to not apply the PST requirements.

2.6 Regulations and Guidelines

The NWP is located in Canadian territorial waters where The Canada Shipping Act is applied. There are several pieces of legislation that govern the shipping in Canadian Arctic. They were created to protect the environment, life, health and property. The ship operators and ship owners are responsible that they comply with all applicable acts and regulations. These regulations are listed as follows: the Canada Shipping Act 2001, the Marine Liability Act, the Marine Transportation Security Act, the Coasting Trade Act and the Canada Labour Code, as well as the Charts and Nautical Publications Regulations, 1995, and Navigation Safety Regulations made pursuant to the Canada Shipping Act. (Canadian Coast Guard, 2002)

2.6.1 Arctic Shipping Pollution Prevention Regulations (ASPPR)

The ship concept is operating in north of latitude 60°N within Canadian jurisdiction, which is governed by the Arctic Shipping Pollution Prevention Regulations (ASPPR), under the Arctic Waters Pollution Prevention Act. ASPPR is applied to ships over 100 gross tons, which requires to govern their construction and operation in the Arctic. In practice this means that the ship must have adequate ice class, ice navigators onboard and Arctic Pollution Prevention Certificates.

The ASPPR uses the Zone/Date system, where the Canadian Arctic waters are divided in total of sixteen zones which are called Shipping Safety Control Zones. Each of these zones has schedule, which is dependent on ships ice class. The schedule of each zone consists of earliest and latest entry date. The zones are sequenced based on the severity of ice conditions from smallest number to largest, meaning that the Zone 1 hast the most severe ice conditions. The Figure 15 presents the map of Canadian Arctic with the Shipping Safety Control Zones and it is designed to be used with the, Table 7 which gives the dates of entry with different ice class categories. However, the table does not show the required Polar Classes even though Transport Canada currently recommends that vessels should not be built with Canadian Arctic Categories (AC & CAC) and supports the full implementation of the Polar Class for new buildings. Using the table an operator can determine the legal periods of entry into the various Zones. (Canadian Coast Guard, 2002)

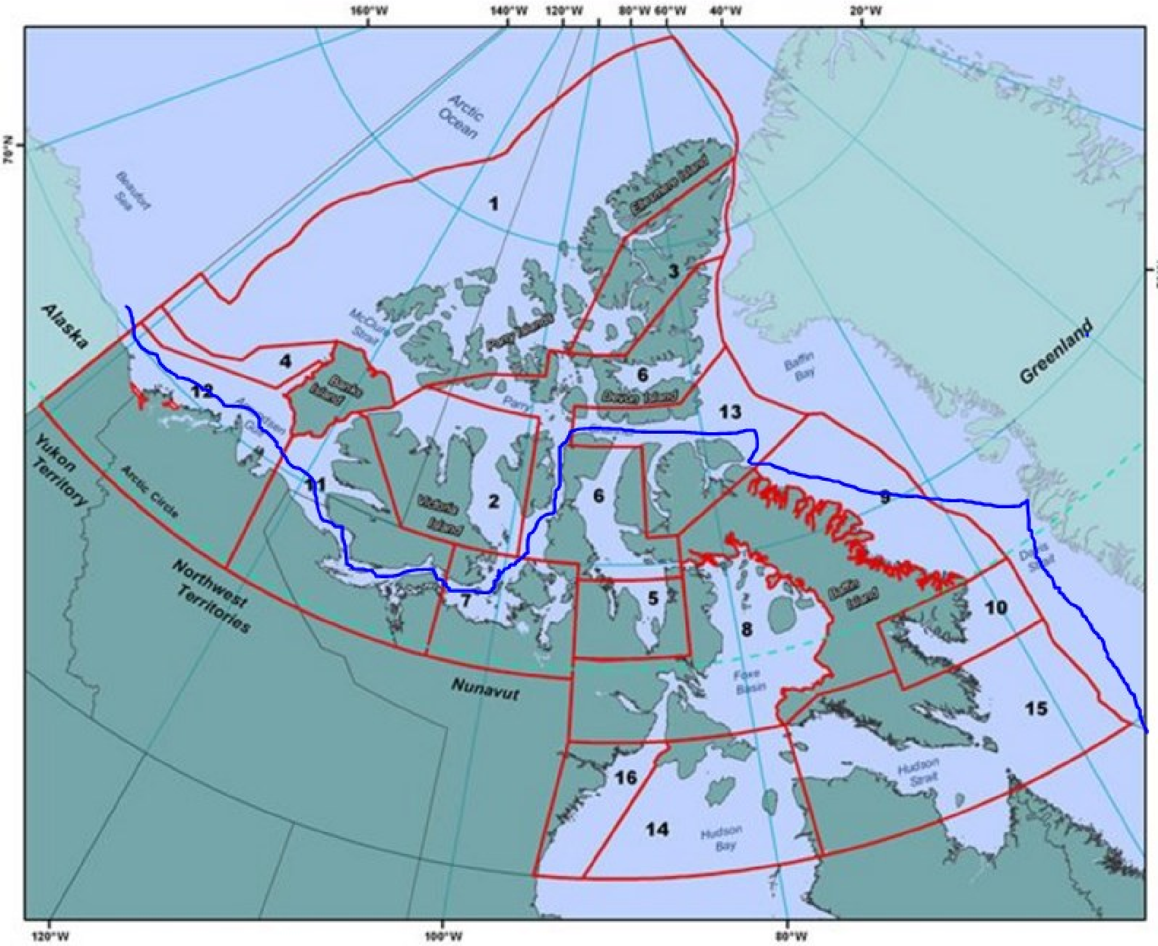


Figure 15. Shipping Safety Control Zones with Serenity cruise route (Canadian Coast Guard, 2002).

Table 7. Dates of entry into shipping safety control zones with old Arctic Class (Canadian Coast Guard, 2002).

Category	Arctic Class 10	Arctic Class 8	Arctic Class 7	Arctic Class 6	Arctic Class 4	Arctic Class 3	Arctic Class 2
Zone 1	All Year	July 1 to Oct. 15	Aug. 1 to Sept. 30	Aug. 15 to Sept. 15	Aug. 15 to Sept. 15	Aug. 20 to Sept. 15	No Entry
Zone 2	All Year	All Year	Aug. 1 to Nov. 30	Aug. 1 to Oct. 31	Aug. 15 to Oct. 15	Aug. 20 to Sept. 30	No Entry
Zone 3	All Year	All Year	July 1 to Dec. 31	July 15 to Nov. 30	July 15 to Oct. 31	July 25 to Oct. 15	Aug. 15 to Sept. 30
Zone 4	All Year	All Year	July 1 to Dec. 15	July 15 to Nov. 30	July 15 to Nov. 15	July 20 to Nov. 5	Aug. 1 to Oct. 31
Zone 5	All Year	All Year	July 1 to Dec. 15	Aug. 1 to Oct. 15	Aug. 15 to Sept. 30	Aug. 20 to Sept. 25	No Entry
Zone 6	All Year	All Year	All Year	July 15 to Feb. 28	July 20 to Dec. 31	Aug. 1 to Nov. 30	Aug. 15 to Nov. 20
Zone 7	All Year	All Year	All Year	July 1 to Mar. 31	July 15 to Jan. 15	July 20 to Dec. 15	Aug. 1 to Nov. 20
Zone 8	All Year	All Year	All Year	July 1 to Mar. 31	July 15 to Jan. 15	July 20 to Dec. 31	Aug. 1 to Nov. 30
Zone 9	All Year	All Year	All Year	All Year	July 10 to Mar. 31	July 20 to Jan. 20	Aug. 1 to Dec. 20
Zone 10	All Year	All Year	All Year	All Year	July 10 to Feb. 28	July 15 to Jan. 25	July 25 to Dec. 20
Zone 11	All Year	All Year	All Year	July 1 to Mar. 31	July 5 to Jan. 15	July 5 to Dec. 15	July 10 to Nov. 20
Zone 12	All Year	All Year	All Year	All Year	June 1 to Jan. 31	June 10 to Dec. 31	June 15 to Dec. 5
Zone 13	All Year	All Year	All Year	All Year	June 1 to Feb. 15	June 10 to Dec. 31	June 25 to Nov. 22
Zone 14	All Year	All Year	All Year	All Year	June 15 to Feb. 15	June 20 to Jan. 10	June 25 to Dec. 10
Zone 15	All Year	All Year	All Year	All Year	June 15 to Mar. 15	June 20 to Jan. 31	June 25 to Dec. 20
Zone 16	All Year	All Year	All Year	All Year	June 1 to Feb. 15	June 5 to Jan. 10	June 10 to Dec. 10

In order to find out what are the dates of entry for Polar Class ships equivalent categories between CAC and PC must be find. Based on the Transport Canada Bulletin No.:04/2009 equivalents between classes is represented in the Table 8. (Transport Canada, 2009b)

Table 8. Comparison between classes.

Category	Equivalent CAC	Equivalent PC
Arctic Class 10	CAC1	PC 1
Arctic Class 8	CAC2	PC 2
Arctic Class 6	CAC3	PC 3
Arctic Class 3	CAC4	PC 4
-	CAC4 – Type A	PC 5

Using the Table 8 Ice Class equivalents, a new Table 9 is formulated with dates of entry into safety control zones, which corresponds with Polar Classes. This is a useful tool when considering suitable Polar Class for the case ship later on. Crystal Serenity's zones are highlighted with green color when she sailed the NWP between the end of August and the halfway of September.

Table 9. Dates of entry with Polar Classes.

Category	PC 1	PC 2	PC 3	PC 4/PC 5
Zone 1	All Year	July 1 to Oct. 15	Aug. 15 to Sept. 15	Aug. 20 to Sept. 15
Zone 2	All Year	All Year	Aug. 1 to Oct. 31	Aug. 20 to Sept. 30
Zone 3	All Year	All Year	July 15 to Nov. 30	July 25 to Oct. 15
Zone 4	All Year	All Year	July 15 to Nov. 30	July 20 to Nov. 5
Zone 5	All Year	All Year	Aug. 1 to Oct. 15	Aug. 20 to Sept. 25
Zone 6	All Year	All Year	July 15 to Feb. 28	Aug. 1 to Nov. 30
Zone 7	All Year	All Year	July 1 to Mar. 31	July 20 to Dec. 15
Zone 8	All Year	All Year	July 1 to Mar. 31	July 20 to Dec. 31
Zone 9	All Year	All Year	All Year	July 20 to Jan. 20
Zone 10	All Year	All Year	All Year	July 15 to Jan. 20
Zone 11	All Year	All Year	July 1 to Mar. 31	July 5 to Dec. 15
Zone 12	All Year	All Year	All Year	June 10 to Dec. 31
Zone 13	All Year	All Year	All Year	June 10 to Dec. 31
Zone 14	All Year	All Year	All Year	June 20 to Jan. 10
Zone 15	All Year	All Year	All Year	June 20 to Jan. 31
Zone 16	All Year	All Year	All Year	June 5 to Jan. 10

There is lots of inter-annual variability in the ice conditions which are not taken into account in the Zone/Date system. There was need for more flexible system and Transport Canada took care of this fault by developing Arctic Ice Regime System (AIRRS) in 1996. The AIRRS takes into account current ice conditions in the planned route outside of the established dates of Zone/Date system, when normally the ship was forbidden to proceed. With this way the ship can operate outside of the established dates safely, and variations of ice conditions are taken into account. (Canadian Coast Guard, 2002) In the Chapter 3.5.1 the AIRSS is explained with more detail level, and also demonstrated for the Polar Class.

2.6.2 Polar Code

The new IMO Polar Code is the answer for the need for comprehensive safety and environmental protection measures based on the precautionary approach and practices. The need for a new mandatory IMO Polar Code was clear since existing international conventions do not include operational conditions like low temperatures and sea ice. “The International Maritime Organization (IMO) Polar Code is a ship focused code with specific provision for ship structure, subdivision, stability, equipment carriage (i.e. life-saving, navigation, and communications), crew training, and environmental protection for ships in the Arctic (N of 60oN) and Antarctic (S of 60oS). Consistent with the other IMO codes (i.e. ISPS Code), the Polar code contains both mandatory and non-mandatory provisions. The Polar Code provisions are additions to IMO Conventions (Safety of Life at Sea (SOLAS), Prevention of Pollution from Ships (MARPOL), and Standard of Training, Certification, and Watch-keeping (STCW) that will take effect through amendment to these instruments. Key provisions of the Code include: Mandatory requirements for Certification, risk assessments, and voyage planning; ice strengthening, cold temperature protection, tank protection, and ice navigation training, where appropriate; and additional restrictions on the discharges of wastes, including zero discharge of oily mixtures.*"* (Arctic Council, 2009)

*"*POLARIS builds on the existing operational limitations in part I-B of the Polar Code by recognizing the limitations and linking the ice conditions in which the ship is intended to operate into ice class assigned to the ship." (IMO, 2015)

Vessel operating in the polar waters should always carry on board Polar Water Operational Manual (PWOM), which provides information, operational assessments and solutions. It is also a guideline for crew to identify a ship's operational capabilities and limitations. (IMO, 2015)

2.7 Use in winter seasons

Since the season is limited in the Northwest Passage to the summer months it is not economical to lay-up the ship during the winter months. One opportunity is to navigate the ship in the Antarctic where the austral summer season begins in late October and lasts until the middle of March. The tourism in Antarctic has increased more than 600% in last twenty years and the most common method for a visit is by a cruise ship departing from South America to visit the Antarctic Peninsula. Antarctic Peninsula is the northernmost part of the mainland of Antarctica. Total number of passengers in the season of 2016-2017 was 44367, which was 15% increase to the previous season. Vast variety of seals, whales and exotic birds like penguins offers attraction for tourism. It is forbidden for passenger ship with more than 500 passengers to make landings in Antarctica, meaning that the ship concept which is considered in the next chapter could only perform scenic cruises. In spite of the latter, there seems to be market for this kind of operations since 17% of seaborne passengers were cruise only without landings giving total of 7475 passengers. (IAATO, 2017) The Figure 16 illustrates a common cruise ship route in the Antarctic.

Figure 16. Cruise ship route to visit Antarctic Peninsula from South America (AdventureSmith Explorations, 2017).

3 The ship concept

Case concept ship is chosen based on Turku shipyard reference cruise ships designed for open water conditions. Turku shipyard is known to build the biggest cruise ships in the world. However, these kinds of ships over 200 000 GT could face serious problems operating in narrow channels of the NWP. The newest cruise ship of Meyer Turku: Mein Schiff 5 (MS 5) is used as a reference ship. It is smaller scale product of the ship-yard with approximately 100 000 GT making it feasible to operate in the NWP. MS 5 has very good energy efficiency because of the state of art technologies and smooth hull form giving a good foundation for the ship concept.

Cruise operations in the NWP will start as early as possible in the summer season aim is to have completely independent operation without assistance of icebreaker. With proper Polar Class the cruise ship can stand out from non-ice strengthened cruise ships offering an early start in the North West Passage. This gives an opportunity for passenger to experience midnight sun and see ship operating in real ice conditions and not just trying to avoid the ice. Different options regarding fuel and design for the ship concept is studied to make it economically feasible and environmentally friendly to protect fragile Arctic ecosystem. In order to fulfill the technical requirements to operate in ice conditions, one must identify operating concept, establish area of operation and identify prevailing ice conditions.

3.1 Main dimensions

Main dimensions are based on Meyer Turku shipyard MS 5. Mein Schiff series produced in Turku shipyard is known to be environmental friendly ship with high range operational autonomy. Turku shipyard has built four Mein Schiff series ships, which has led to a sophisticated product. With the use of the newest Mein Schiff as a reference shipyard can save production and design costs significantly and customer satisfaction is also guaranteed. Table 10 below shows the main characteristics of MS 5.

Table 10. Main characteristics of MS 5.

Length over all	295 m
Length between perpendiculars	273 m
Breadth, moulded	36 m
Draught, moulded max	8.25 m
Life Saving Equipment Capacity	3820 persons
Max number of passengers	2794 persons
Number of passenger staterooms	1267 pcs
Number of crew	(996 crew + riding crew) 1026 persons)
Number of crew cabins	600 pcs
Main machinery power	48 000 kW
Propulsion power	2 x 14000 kW
Bow thrusters	3 x 3000 kW
DWT	7900 Tonnes
Fuel Oil	1500 Tonnes

3.2 Polar classes

Purposes of the Polar Classes were to make unified ice class rules for ships intended to operate independently in ice-infested polar waters. These rules were introduced back in 2006 by the International Association of Classification Societies (IACS). The adoptions of the Polar Classes standardized the system since all the classification societies had their own rules for ships operating in the Polar Waters. Polar code divides ships into three categories: A, B and C which are linked to ice class notations and provide a broad indication of a ship's capability to operate in ice. Polar classes from PC 1 – PC 5 are in the category A and PC 6 – PC 7 are in the category B. (ABS, 2016)

Table 11. Polar Class descriptions.

Polar class	Ice Description
PC 1	Year-round operation in all Polar Waters
PC 2	Year-round in moderate multi-year ice conditions
PC 3	Year-round in Second-year ice with Old ice Inclusions
PC 4	Year-round operation in thick, First-year ice with Old ice inclusions
PC 5	Year-round operation in medium, First-year ice with Old ice inclusions
PC 6	Summer/autumn operation in medium, First-year ice with Old ice inclusions
PC 7	Summer/autumn operation in thin, First-year ice with Old ice inclusions

Polar Class notation PC 1 through PC 5, bows with vertical sides, and bulbous bows are generally to be avoided.

There are no power requirements to the machinery, but the hull form and propulsion power should be adequate that the ship can operate independently with continuous speed on ice conditions, as defined in polar class descriptions. However, there are requirements for the strength of the propulsion system to withstand the ice induced loads.

The Figure 17 represents hull areas which are divided based on magnitude of loads, which are expected to act upon them. There are four regions in longitudinal direction: Stern, Midbody, Bow Intermediate and Bow. The Bow Intermediate, Midbody and Stern are also divided in the vertical direction into the Bottom, Lower and Icebelt regions.

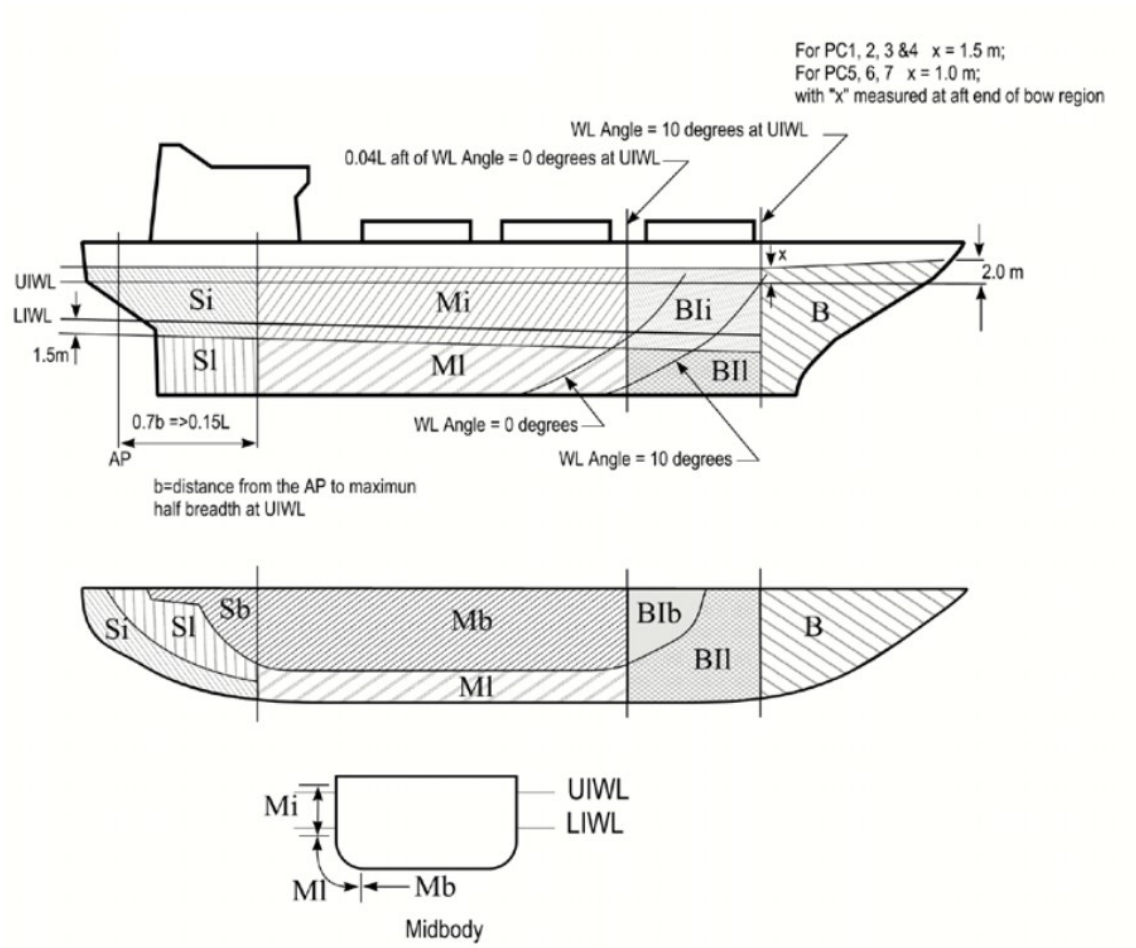


Figure 17. Hull area extents (IACS, 2011).

3.2.1 Design methodology

In the IACS Requirements for PC the ice loads at bow are determined as a function of bow shape. There are different equations for bow area depending on if the bow is meant to break the ice or not based on the angles of bow. In the other areas of the hull ice loads are determined based on table values, which are independent of the hull shape. The plating and framing requirements are based on plastic response criteria. If overall strength or watertight integrity of the ice class ship is not compromised, occasional local deformation has tended to be an acceptable consequence in ice operations. With the use of plastic design a better balance of material distribution can be achieved to resist design and extreme loads. Ice loads can exceed the design values considerably and with the use of plastic design a sufficient strength reserve is ensured. However the selection of structural design criteria for plastic design is more challenging than in elastic design. The elastic design is based on yield which is relatively easy to predict, giving a simple criterion for design. On the contrary in plastic design there are many possible limits ranging from yield through to final rupture. (Daley *et al.*, 2001)

In the unified rules (UR) the limits states are idealized plastic collapse onset mechanisms, which are simplified and uses conservative assumptions. For example, strain hardening and membrane stresses are ignored even though they would have positive effect. Consequently, a high reserve capacity can be expected to the structure, but the design limits are selected to represent a condition of substantial plastic stress, which would develop large plastic strains and deformations. (Daley *et al.*, 2001)

3.2.2 Shell plating requirements

The Figure 18 represents the onset of plating collapse by the formation of a set of plastic hinges. The numerical solution shows that in general the failure area is approximately equal to the load height. Equations are derived using this assumption.

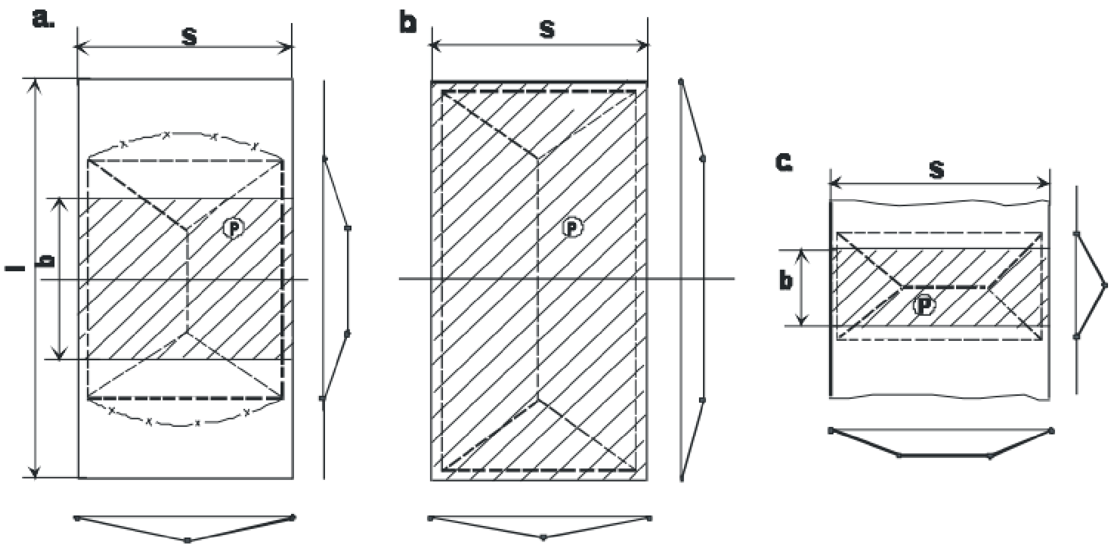
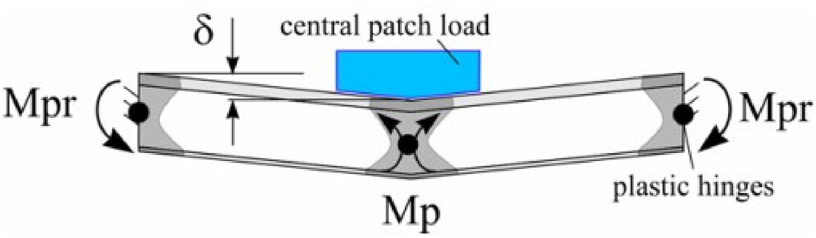


Figure 18. Plating collapse mechanisms (Daley *et al.*, 2001).

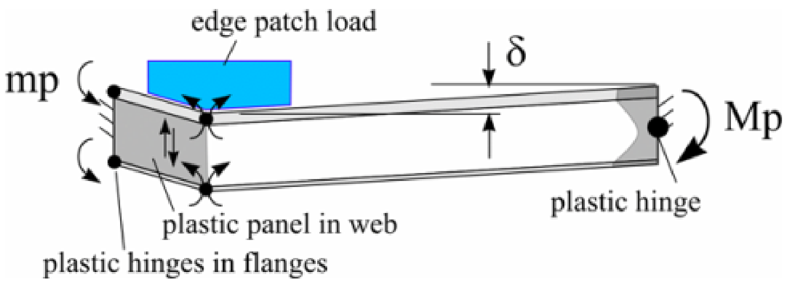
The required thickness of the shell plating consists of the plate thickness required to resist ice loads t_{net} and corrosion/abrasion allowance t_s. The corrosion allowance is dependent on the area, the Polar Class and the effective protection. The thickness of the shell plating required to resist the design ice load, t_{net} depends on the orientation the framing. (IACS, 2011)

3.2.3 Framing

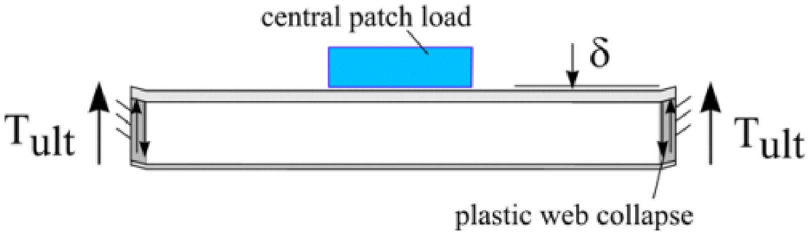
There are three different plastic collapse mechanism considered which determine the three limit states considered in the URs. These collapse mechanisms are illustrated in the Figure 19. Each of these mechanisms can be solved with energy methods by equilibrating internal and external load. (Daley *et al.*, 2001)



(a) 3 Hinge collapse



(b) asymmetric shear collapse



(c) web collapse

Figure 19. The 3 limit states considered for frames (Daley *et al.*, 2001).

Two of these failure mechanisms recognize an interaction between shear and bending. Due to latter the framing design can be executed with various ways, which results that designer must understand these interactions in order to make an optimal design. (Daley, 2002) The Polar Class rules requires that one must calculate the actual shear area as fitted A_W and the actual plastic section modulus of frame as fitted Z_p (see equation 7) and the minimum requirements A_t and Z_{pt} to them. (IACS, 2011)

$$Z_p = \frac{h_w^2 \cdot t_{wn} \cdot sin\varphi_w}{2000} + A_{fn} \cdot (h_{fc} \cdot sin\varphi_w - b_w \cdot cos\varphi_w)/10, cm^3 \qquad (1)$$

Also if the cross-sectional area of the local frame exceeds the cross-sectional area of the attached plate flange, the plastic neutral axis is located a distance z_{na} above the attached shell plate.

$$z_{na} = \frac{100 \cdot A_{fn} + h_w \cdot t_{wn} - 1000 \cdot t_{pn} \cdot s}{2 \cdot t_{wn}}, mm \qquad (2)$$

and the net effective plastic section modulus, Z_p is given by:

$$Z_P = t_{pn} \cdot s \cdot \left(z_{na} + \frac{t_{pn}}{2}\right) \cdot sin\varphi_w + \left(\frac{\left((h_w - z_{na})^2 + z_{na}^2\right) \cdot t_{wn} \cdot sin\varphi_w}{2000} + \frac{A_{fn} \cdot ((h_{fc} - z_{na}) \cdot sin\varphi_w - b_w \cdot cos\varphi_w)}{10}\right), cm^3 \qquad (3)$$

Usually lightest framing is achieved by tallest possible frame with greatest possible modulus for a given web area. However, these kinds of tall web designs can cause buckling. Therefore the requirements prevent this kind tall web designs by equation where the thickness, height of the web and flange yield strength is taken into account to prevent buckling. Furthermore all of the ice framing structures must have 1 mm corrosion allowance. (Daley, 2002)

3.3 Validation of a Polar Class

In the preliminary phase the idea was to apply PC 4 to the vessel since the level ice breaking capacity is higher and possibility to start the operations earlier than other cruise ships in the area. Idea was to stand out from other cruise ships by giving opportunity for passengers to experience real ice conditions and also benefit longer daylight including midnight sun. However, all the options are kept open and feasibility study regarding to polar classes must be made before final decision.

As showed in earlier chapters the ice conditions vary a lot annually in the Northwest Passage. As design basis, the simplest way is to define the max level ice thickness where the vessel can proceed ahead. Also Polar Code risk index outcome (RIO) calculations can be used as a backup for validation process.

From the Figure 9 and Figure 10 it can be determined that the level ice thickness can be around 150 cm at the beginning of June, when the operation period is planned to begin. Consequently the Polar Class must withstand 1.5 m level ice operations. Guidance relating to the ice class determination was also sought from Transport Canada, who is responsible of the Arctic operations in their territorial waters. They agreed with the preliminary selection of PC 4, by reasoning that PC 5 would be burdened with further operational limitations. However, with the estimated time window and ice conditions, there is no reason to exclude PC 5 and it would be more profitable option for the ship-owner due to lower capital and operational costs. The Figure 20 shows that PC 5 can operate in 1.2 m thick level ice without restrictions and up to 3 meters thick level ice with slow speed. With the maximum icebreaking capability of 1.5 m at the speed of 2 knots, the PC 5 wouldn't form a problem. PC 6, which is equivalent for Finnish-Swedish Ice Class Rules (FSICR) 1A Super, wouldn't fulfill the requirements in the area selected time window. Higher Polar Classes were not considered since higher costs and limited benefits in operations.

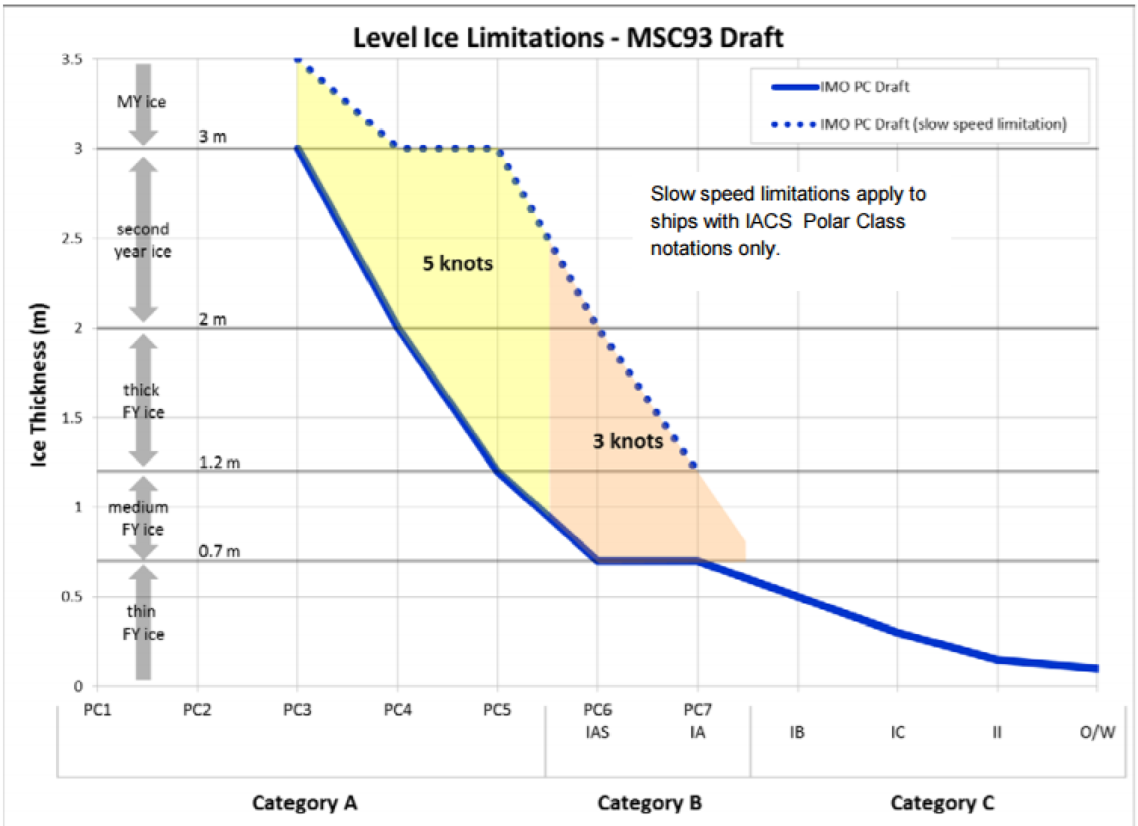


Figure 20. Limitations for level ice (IACS, 2014).

3.3.1 AIRSS Calculation for worst case scenario

Using the four-step of AIRRS, the ship operator is able to estimate if the ship is able to operate in the prevailing ice conditions or not.

First, the ice regime on the planned route is characterized. It is based on WMO Egg Code which takes into account ice regimes age, state of decay, thickness, roughness and concentration in tenths. Ice regime can be defined as a region of a sea where ice is present more or less.

Second, based on the ships ice class and ice conditions the vessel is ranked using Ice Multipliers (IM). Ice Multipliers take into account the ice type and the ships ice class, which estimates the relative damage risk.

Third, when the ice concentration for the different ice types is multiplied with the ice multipliers present the Ice Numeral (IN) is determined. It is simple calculation which presents the operation risk of the ship in different ice regimes.

Finally, one is able to determine based on ice numeral, whether the ship is able or not to operate in the prevailing ice conditions. If the ice numeral is positive or zero, the ice regimes won't possess high operation risks. In the case of negative ice numeral, the ice regime can be dangerous and ship's master must consider, if the ship should proceed or take an alternative route. (Transport Canada, 1998) The Table 12 shows the ice multipliers, which are used to forms ice numeral.

Table 12. Ice Multipliers for AIRSS.

Ship Category	Open Water	Grey Ice	Grey White Ice	Thin First Year Ice, 1st	Thin first Year Ice, 2nd Stage	Medium First Year Ice	Thick First Year Ice	Second Year Ice	Multi-Year Ice
CAC 3	2	2	2	2	2	2	2	1	-1
CAC 4	2	2	2	2	2	2	1	-2	-3
Type A	2	2	2	2	2	1	-1	-3	-4
Type B	2	2	1	1	1	-1	-2	-4	-4
Type C	2	2	1	1	-1	-2	-3	-4	-4
Type D	2	2	1	-1	-1	-2	-3	-4	-4
Type E	2	1	-1	-1	-1	-2	-3	-4	-4

Using ice multiplier table AIRSS can be used similarly as POLARIS. With the PC 5 the ship concept roughly corresponds to Type A / CAC4 vessel and PC 4 corresponds to CAC4. Type A vessel is based on Finnish-Swedish Ice Class Rules, where the ship can operate in thick FYI. This kind of vessel is not as structurally capable as PC 5 vessel.

Table 13. Ice Numerals for PC 4 and PC 5 vessels in years 2004 and 2008.

Month	January		February		March		April		May		June	
Year	2004	2008	2004	2008	2004	2008	2004	2008	2004	2008	2004	2008
Egg Code	9+ 1. 6	10 1. 8	10 4. 8	10 8 2 4 1. 6 8	10 4. 8	10 4. 8	10 4. 8	10 4. 8	10 4. 8	10 4. 8	10 4. 8	10 4. 8
IN PC 4	20	20	10	20	10	10	10	10	10	10	10	10
IN PC 5	10	10	-10	18	-10	-10	-10	-10	-10	-10	-10	-10
Month	July		August		September		October		November		December	
Year	2004	2008	2004	2008	2004	2008	2004	2008	2004	2008	2004	2008
Egg Code	10 4. 8	9- 4. 6	10 4. 8	5 4. 5	9+ 2 3 5 7. 4 1 4 4 X	9+ 6 2 2 7 4. 1 5 4 X	9+ 4 6 9. 7 6 6	9+ 4 1 5 9 8. 5 6 4 5	9+ 3 5 2 9 8. 7 5 5 5	9+ 2 8 9. 7 5 5	10 3 5 2 9 8. 7 5 5 8	10 1. 8
IN PC 4	10	10	10	15	12	18	0	16	0	10	0	20
IN PC 5	-10	-10	-10	5	10	14	-4	15	-5	8	-5	10

The Table 13 shows that values are negative with PC 5, if it is considered to be Type A vessel. However, PC 5 can be considered to be equivalent to CAC4, which gives positive values. The use of AIRSS is problematic for Polar Class vessels, and use of POLARIS is more preferable option.

3.3.2 POLARIS Calculation for worst case scenario

POLARIS uses a Risk Index Outcome (RIO) value to assess limitations for operation in ice. To support the selection of an ice class an evaluation with RIO is executed with worst case scenarios in selected time window in the Northwest Passage. POLARIS can be used this way for regulation purposes to find out how the selected ice class manages in corresponding ice conditions. (IMO, 2015)

Application of the POLARIS RIO system has been studied by Finnish scientist from Aalto University. Purpose was to study ice-induced loads onboard in the Antarctic and used these values to analyze application of the POLARIS. The ice conditions at the time were significantly more severe than in the chosen time window at the NWP. The Figure 21 presents the ice thickness in each observation period.

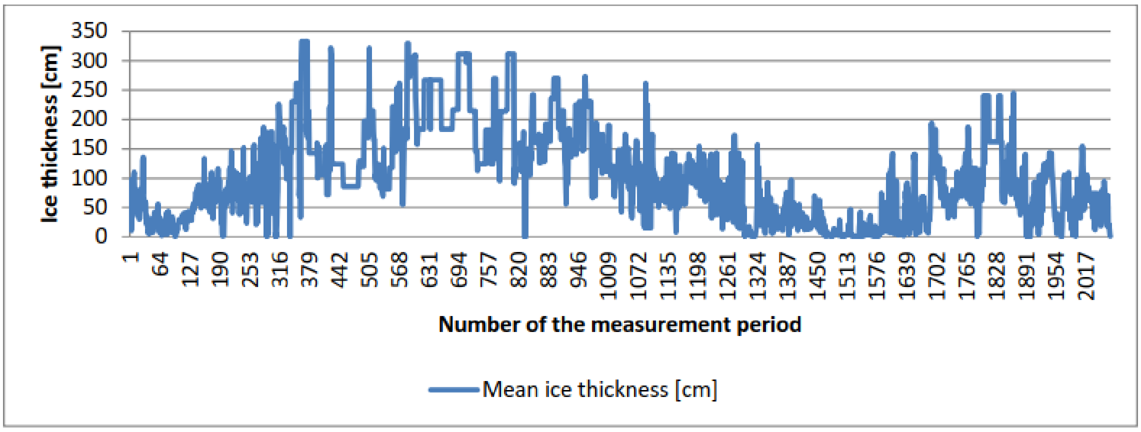


Figure 21. The mean ice thickness in each observation period (TraFi & Kamarainen, 2015).

Comparison of ice load measurements with the design ice loads of ice classes PC 3, PC 5 and IA Super was made in this study, which can be used to support the validation of the case ships ice class. The ship itself S.A Agulhas II has a DNV ICE 10 ice class, which is roughly equivalent to the PC 3. Result of the study was that the measured ice loads were very much in line with the POLARIS calculations. With the way the ship was operated the ice loads were clearly exceeded for the hull strength of ice class IA Super, and slightly exceeded of ice class PC 5, and the chosen ice class DNV ICE 10 withstands well the measured ice loads. Study also revealed that the exceedances would most probably have caused permanent deflections in the PC 5 ship's hull, but the ship would have survived. These results are encouraging since the calculated RIO values for PC 5 were occasionally close to -20, which means that the operation is subject to special consideration if RIO < -10. The Figure 22 presents the RIO values for PC 5, since it is the most probable ice class for the case ship. (TraFi & Kamarainen, 2015)

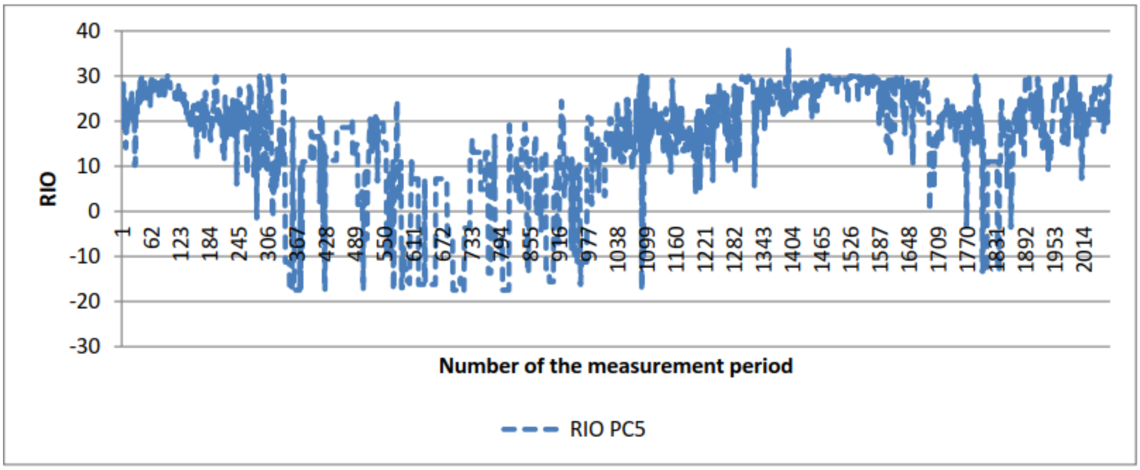


Figure 22. Results of the POLARIS calculations for ice class PC 5 (TraFi & Kamarainen, 2015).

Applicability of POLARIS was also studied with Oil Tanker MT Uikku in Kara Sea. Ice loads measured onboard compared with POLARIS RIO values gave strong evidence that POLARIS gives reliable estimates of safety levels with chosen ice class in various ice conditions. (Kujala & Suominen, 2016)

In order to evaluate the applicability of the PC 4 and PC 5 in the case ship more ice conditions investigation is required. RIO can be performed with the ice data presented in Egg Code format from the ice charts. In order to execute RIO, ice charts must be studied to find the harshest ice conditions in operation period from the beginning of June at the end of October. As earlier in the chapter 2.5.1 presented, the ice conditions were most severe in the years 2004 and 2008, measured in Resolute and Cambridge Bay. However, in this consideration only ice thickness was taken into account without composition, which is crucial factor when estimating the risks. Canadian ice service provides ice charts where the ice conditions are presented in Egg Code format. Ice charts are studied in years 2004 and 2008 (see Appendix 1) following the route of Crystal Serenity, and the most severe ice regimes are collected in a monthly level.

As earlier in the Figure 8 explained, determination of the ice conditions can be made using aid from the Table 4 and Table 5.

In order to evaluate the risk using the Risk Index an overall outcome for each ice regime can be calculated, now using POLARIS nomenclature:

$$RIO = (C_1 \times RV_1) + (C_2 \times RV_2) + \cdots + (C_n \times RV_n) \quad (4)$$

Where
RIO is the Risk Index Outcome
$C_1 \ldots C_n$ are the concentrations (in tenths) of ice types within the ice regime
$RV_1 \ldots RV_n$ are the corresponding Risk Index values for the ship's ice class.

The Table 14 shows the evaluation criteria for ships operating independently, based on calculated RIO values. (IACS, 2014)

Table 14. Risk Index Outcome evaluation criteria (IACS, 2014).

RIO SHIP	Category A & B (PC1-PC7)	Category C (below PC7)
RIO ≥ 0	Operation Permitted	Operation Permitted
-10 ≤ RIO < 0	Limited Speed Operation Permitted	Operation Not Permitted
RIO < -10	Operation Not Permitted	Operation Not Permitted

In the POLARIS procedure there are set two seasons with different Risk Indices: ''summer'' and ''winter''. Winter values (see Table 15) are retained year-round unless there is definitive local data / reporting that ice decay has occurred – this reflects the local seasonal variability of ice decay in the Arctic. On the other hand Canadian approach has been that the summer season is from July to September. Nevertheless winter values are used in this case because there is no knowledge of ice decay.

Table 15. Risk Index Values - Winter Conditions (IACS, 2014).

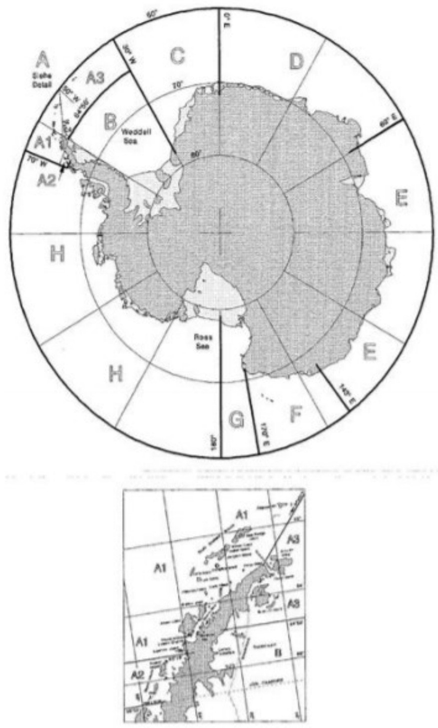
Category	Ice Class	Ice Free	New Ice	Grey Ice	Grey White Ice	Thin First Year Ice, 1st	Thin first Year Ice, 2nd	Medium First Year Ice	Medium First Year Ice, 2nd	Thick First Year Ice	Second Year Ice	Light Multi-Year Ice	Heavy Multi-Year Ice
A	PC 1	3	3	3	3	2	2	2	2	2	2	1	1
	PC 2	3	3	3	3	2	2	2	2	2	1	1	0
	PC 3	3	3	3	3	2	2	2	2	2	1	0	-1
	PC 4	3	3	3	3	2	2	2	2	1	0	-1	-2
	PC 5	3	3	3	3	2	2	2	1	0	-1	-2	-2
B	PC 6	3	2	2	2	2	1	1	0	-1	-2	-3	-3
	PC 7	3	2	2	2	1	1	0	-1	-2	-3	-3	-3
C	1A Super	3	2	2	2	2	1	0	-1	-2	-3	-4	-4
	1A	3	2	2	2	1	0	-1	-2	-3	-4	-4	-4
	1B	3	2	2	1	0	-1	-2	-3	-3	-4	-5	-5
	1C	3	2	1	0	-1	-2	-2	-3	-4	-4	-5	-6
	No Ic	3	1	0	-1	-2	-2	-3	-3	-4	-5	-6	-6

The Table 15 reveals that the risk index values for PC 4 are only negative when multi-year ice condition are present and for PC 5 also the second year ice gives negative values. This means that RIO is always positive for PC 4 if the ice regime concentrations mainly consist of other than MY ice. To find out how the operation season is limited by RIO, ice conditions are studied in years 2004 and 2008 (see Table 16). Even if the results were positive, it doesn't mean that the ship can operate the whole year, because the icebreaking capability is limited to 1.42 meter first year level ice. The RIO value gives only guidance, whether ship is allowed to operate in the current conditions and the validation of ice class shouldn't completely be based on the RIO values.

Table 16. Most severe ice regimes in selected operation season in years 2004 and 2008.

Month	January		February		March		April		May		June	
Year	2004	2008	2004	2008	2004	2008	2004	2008	2004	2008	2004	2008
Egg Code	9+ / 1. / 6	10 / 1. / 8	10 / 4. / 8	10 / 8 2 / 4 1. / 6 8	10 / 4. / 8	10 / 4. / 8	10 / 4. / 8	10 / 4. / 8	10 / 4. / 8	10 / 4. / 8	10 / 4. / 8	10 / 4. / 8
RIO PC 4	20	20	10	12	10	10	10	10	10	10	10	10
RIO PC 5	10	10	0	2	0	0	0	0	0	0	0	0
Month	July		August		September		October		November		December	
Year	2004	2008	2004	2008	2004	2008	2004	2008	2004	2008	2004	2008
Egg Code	10 / 4. / 8	9- / 4. / 6	10 / 4. / 8	5 / 4. / 5	9+ / 2 3 5 / 7. 4 1 / 4 4 X	9+ / 6 2 2 / 7 4. 1 / 5 4 X	9+ / 4 6 / 9. 7 / 6 6	9+ / 4 1 5 / 9 8. 5 / 6 4 5	9+ / 3 5 2 / 9 8. 7 / 5 5 5	9+ / 2 8 / 9. 7 / 5 5	10 / 3 5 2 / 9 8. 7 / 5 5 8	10 / 1. / 8
RIO PC 4	10	10	10	20	24	20	4	23	10	12	10	20
RIO PC 5	0	0	0	0	22	18	4	22	1	12	1	10

The Table 16 shows that PC 4 values are always above zero and PC 5 gives no values under zero. These values and earlier studies fundamentally verify that PC 5 is feasible in the NWP with the decided time window from beginning of June at the end of October.



Polar Class*	PC 7	PC 6	PC 5	PC 1- 4
Similar other classes	Russian A2; ABS Type B; Swedish 1 A; GL E3	Russian A1, ABS Type A, Swedish 1A Super; GL E4	Russian Y AA; ABS A2; GL ARC 2-3	Russian LL1-3; LR AC3-AC1
Zone	Navigational Period			
A1	1.12.-20.02.	1.12.-20.2.	all year	all year
A2	1.12.-20.02. only seawards off islands	1.12.-20.2.	all year	all year
A3	1.1.-20.2., if ice coverage < 5/10	1.12.-20.2.	1.10.-30.4. W-wards from 40° W; all year E-wards from 40° W	all year
B	never	1.1.-20.2. except in SW quadrant	all year in NE and SE quadrant; 1.1.-20.2. in NW + SW quadrant	all year
C	1.1.-20.2.	1.12.-20.2.	all year N-wards from 70° S; 1.10.-15.3. S-wards from 70° S	all year
D	1.12.-20.2. N-wards of line Erskine Iceport - Amundsen Bay		all year N-wards of line Erskine- Amundsen; 1.10.-30.4. everywhere	all year
E	1.1.-20.2. N-wards of West+ Shackleton ice shelf	1.12.-20.2. N-wards of West+ Shackleton ice shelf	all year N-wards of West +Shackleton ice shelf; 1.12.-30.4. everywhere	all year
F	never if ice coverage >5/10	1.1.-20.2. N-wards of line Balleny	all year N-wards of line Balleny; 1.1.-20.2. everywhere	all year
G	1.1.-20.2.	1.12.-20.2.	all year	all year
H	never if ice coverage >5/10	1.12.-20.2 N-wards of line Adelaide Isld-75°S/160°W	all year N-wards of line Adelaide Isld. - 75°S/160°W; 1.10.-30.4. everywhere	all year

Figure 23. Ice class requirements for safe navigation in the Antarctic Ocean (Nyseth & Bertelsen, 2014).

The Figure 23 shows that the PC 5 ice class is adequate for all year operation in Antarctic Peninsula where the most of the cruise shipping is concentrated. On a recent master thesis by Kantonen, 2016, operational limits for different ice classes in Antarctica region were studied. The study was based on ice thickness simulation methods and POLARIS RIO values. The study showed that ice class PC 5 had no limitations in the austral summer period which lasts from late October until middle of March. In this season also the MDLT stays above -10˚C meaning that there are no PST requirements.

3.3.3 Polar Class structure analysis

As it was earlier determined, the ship is DAS modification of the MS 5. MS 5 has no ice class and structure modifications must be made in order to meet the requirements of Polar Class 5. This ensures safe operation in the area, but will increase the ships weight and cost. Extra high strength steel with yield strength of 490 MPa in the shell plating is used to minimize the weight increase. Using a high strength steel ship's weight can be decreased 5-20 % and cost 0-5 % (Ilus, 1998). Calculations for the structures are made with the DNV GL's ship structural analysis and design program Nauticus Hull. In each hull area extent (See Figure 24) one web frame is dimensioned according to PC 5 rules. In the midship section also PC 4 is dimensioned in order compare in weight to PC 5. Dimensions of MS 5 original structures are erased due to confidentiality. These structures could be also used in the ice breaking bow version, even though the DAS has heavier ice strengthening requirements in the aft area. Even though it is not required in Polar Class requirements, in practice the ship equipped with Azimuth propulsion system, these heavier aft area structures should be applied. When turning in ice conditions using Azimuth propulsion, the aft part of the ship strives to push itself opposite direction than turning, causing high loads in aft areas (Vanne, 2017).

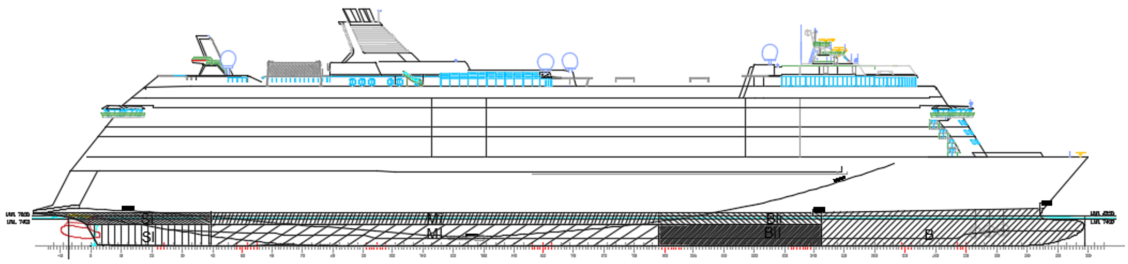


Figure 24. Hull area extents of a case ship.

The Figure 24 shows the hull areas which must be strengthened according to IACS Polar Class requirements.

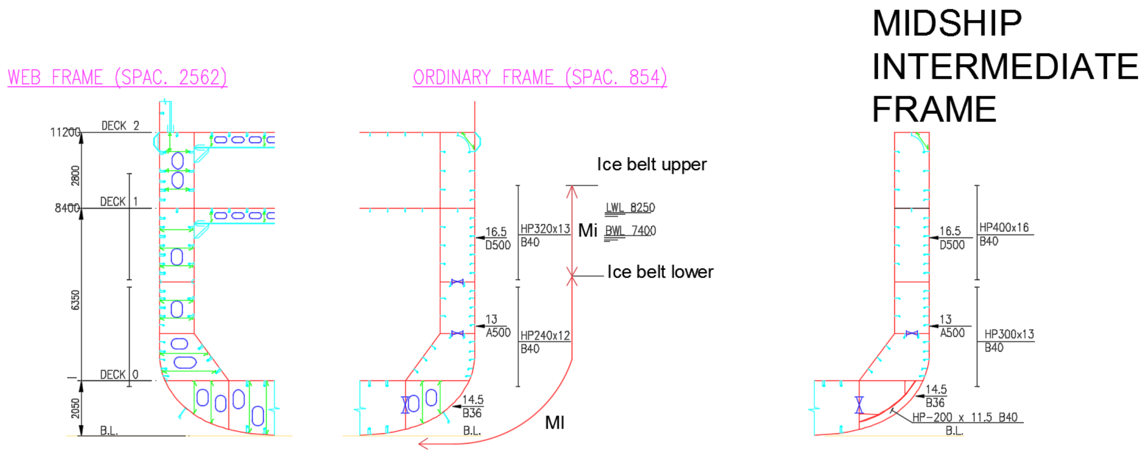


Figure 25. Midship section.

The Figure 25 shows the midship section. Ice strengthening in the area is divided in to two parts, midbody icebelt and midbody lower. There is no ice strengthening requirements in midbody bottom. Framing is longitudinal except in the bilge area, where there are intermediate transversal frames to support the original plate structure. Shell plating is extra high strength steel apart from the bilge area, where the thickness would fall below the class rules minimum requirement of 13 mm of thickness.

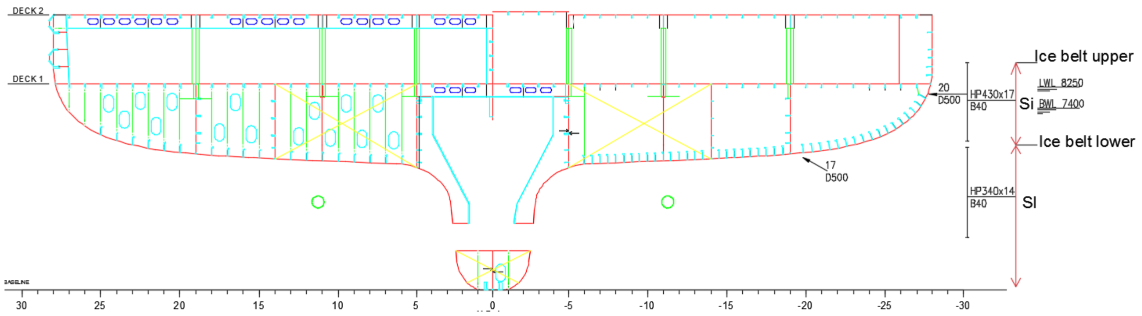


Figure 26. Stern section.

The Figure 26 shows the stern section. The area is divided also in two areas, the stern intermediate icebelt and stern intermediate lower. Because the ship is double acting, the stern is reinforced heavily. In the keel area there is no need for extra steel because the area has been strengthened heavily due to need of docking and thrusters. The stern area is framed longitudinally.

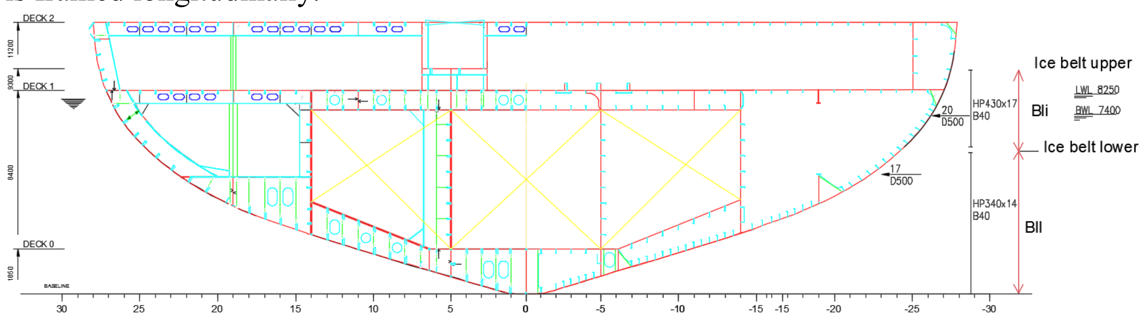


Figure 27. Bow intermediate area.

The Figure 27 shows the bow intermediate area. From the figure it can be seen that the lines are curved and there are no flat bottom. Area is framed longitudinally and extra high strength steel has been used in the whole ice strengthened shell area.

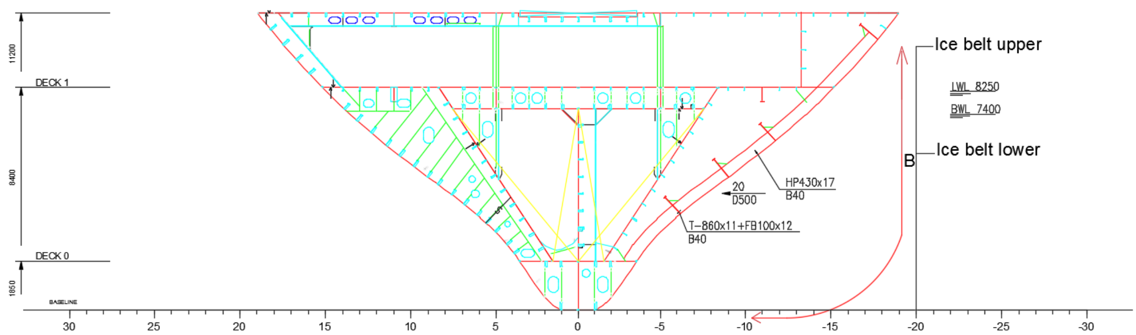


Figure 28. Bow section.

The Figure 28 shows the bow section, where the ice loads are the highest. This is the only area where the hull shape has been taken into account when calculating the ice loads. The bow area is not divided in to different sections and it is framed transversally and stringers are used to divide the loads.

3.4 Ships performance in ice

The most important parameters for ice resistance are the beam B and the stem angle φ. As a result narrower ships with a large L/B ratio has smaller ice resistance, thus it has better ice breaking capability. When it comes to bow shape there are several options to consider which balance between icebreaking capability and open water resistance. (Eronen, 2017) The aim for the ship concept is to be able to break 1.4 level ice in order to start the operations in June.

3.4.1 Breaking ice with bulbous bow

Bulbous bow is a bow shape to reduce drag by modifying water flow around the hull. It can increase the fuel efficiency by twelve to fifteen percent. It can be also used in ice conditions and breaking the level ice, but it must be strengthened and ice breaking capability is lower than traditional ice breaking bow. Breaking level ice with a bulbous bow designed for open water conditions works by bending ice upwards when bow draught is selected suitably. This is optimal for cruise ships as they have a stable draught. Estimate of ice thickness breaking capability for case cruise ship is made based on full scale ice trials of Brage Viking in the Gulf of Bothnia 2013 (Eronen & Vedenpää, 2013). The Table 17 presents a comparison between offshore supply vessel Brage Viking and the concept ship.

Table 17. Comparison between Brage Viking and the Case Ship.

	Brage Viking	Concept Ship
Propulsion power	14Mw	2x14Mw
Breadth	22m	35.8m
Power/Breadth	0.636Mw/m	0.782Mw/m

The table shows that the case ship has approximately 20% more Power/Breadth ratio. However, Brage Viking has ducted propellers, which gives more thrust in pollard bull condition making these vessels comparable. With the known data and with the help of Figure 29 it can be determined that the Case Ships limit thickness in level ice is roughly

1 meter ice with bulbous bow. Limit thickness in level ice is, max level ice thickness where the vessel can proceed continuously ahead with corresponding min speed, normally 1.5-3 knots. (Riska, 2010)

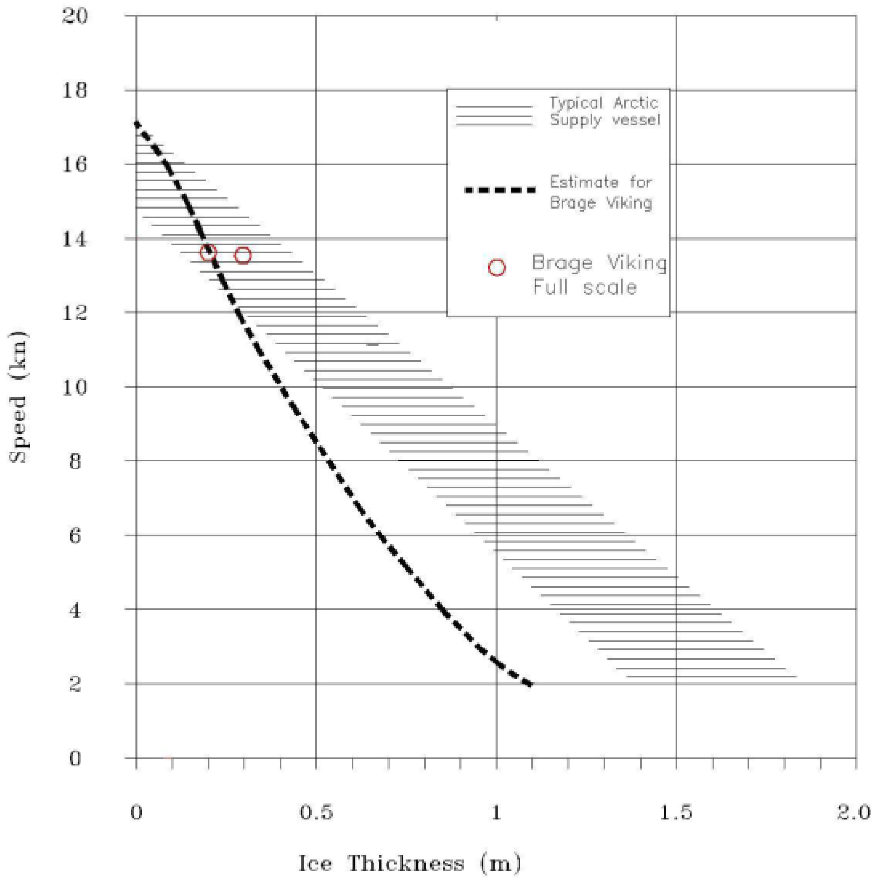


Figure 29. The speed-ice thickness curve for Brage Viking (Eronen & Vedenpää, 2013).

3.4.2 Ice breaking bow

Better icebreaking capability can be achieved by using traditional bow shape without bulbous bow. Bulbous bows are generally to be avoided in Polar Class notation PC 1 through PC 5. (IACS, 2011) Ice breaking capability for first approximation can be calculated with equation 5. (Tsoy *et al.*, 1999)

$$h_i = \frac{0.07 cos^{\frac{3}{2}} \varphi sin^{\frac{1}{2}} \left(\frac{\alpha_0 + \beta_0 + \beta_2}{3}\right)}{\sqrt[2.6]{f_d} \sqrt[5]{L/B} sin^{\frac{3}{2}}(90° - \beta_{10})} \sqrt{P_e/B} \sqrt[6]{D}, \mathrm{m} \quad (5)$$

Where

φ – stem angle, deg	25
α_0 – entrance angle of design water line, deg	30
β_0 – flare angle of frame line No.0[1], deg	50

β_2 – flare angle of frame line No.2, deg	30
β_{10} - flare angle amidships, deg	0
L – vessel's length on DWL, m	270
B – vessel's breadth on DWL, m	35.8
P_e – total propeller bollard thrust, t	304
D – vessel's designed displacement, t	50763
f_d – coefficient of the dynamic ice/ship's hull friction	1

Values recommended of f_d parameter:

- for stainless steel -0.065,
- for Inerta-160 coating -0.072,
- for typical shipbuilding steel -0.080.

Total propeller thrust needed for the calculation of the icebreaking capability under conditions close to the bollard pull mode of operation may be calculated by the formula based on the experience of the design of domestic icebreakers:

$$P_e = k_p(dN_p)^{2/3}, \text{ kN} \quad (6)$$

Where

N_p – total shaft power, 28000 kW
d – Propeller diameter, 6 m
k_p – coefficient taking into account geometric characteristics of propellers, their number and interaction with the ship's hull; depending on the number of propellers this coefficient takes the following values: for triple-shaft ship -1.12, for twin-shaft ship -0.98, for single shaft ship -078. In case twin-shaft ship as MS5 has 0.98 is used giving total bollard pull of 304 kN.

The equation 6 gives 1.48 m level ice breaking capability with the given data. Values for icebreaking bow were chosen based on Russian atomic lighter carrier NS Sevmorput which has relatively similar characteristics than the case ship (see appendix 2). (Tsoy *et al.*, 1999)

3.4.3 Double acting version

The DAS (double acting ship) consist of an ice-going ship with a podded propulsion and optimized stern for operations in heavy ice stern first. This gives an opportunity to have bow shape optimized for open water and even use a bulbous bow. With this way it can solve the problem between open-water and ice performance. The stern area must be reshaped for the double acting operation, which would probably increase the open water resistance. Astern mode is only used in heavy ice conditions. When operating in astern mode, the azimuth propulsion breaks and clears ice with the wake of its propellers. In lighter ice conditions ahead mode is more beneficial, because of the lower open water resistance. In partially concentrated and lighter ice regimes ahead mode is used. Bow thrusters can be used to assist maneuvering astern first, but low speed is required, because thruster efficiency is lost in higher speeds. Also bow thrusters must be ice strengthened and protected with grids. (Eronen, 2017)

In order to make the DAS possible aft body lines must be modified and possibly increase ships draft. Clearance between propeller and hull must be adequate minimizing interaction between propeller and ice floes. Normally this clearance is the maximum ice thickness in the operation so in this case of 1.4 m. Transom angle is important parameter when operating astern. The vertical transom of MS 5 must be modified, because with current design it would stop the vessel backing in the ice. This kind of modification would increase the open water resistance of the ship, but this hasn't been taken into account later on when calculating the fuel consumptions. (Eronen, 2017) Additionally there must be another bridge located in the stern where the crew can operate the ship in double acting mode. This kind of arrangement will most likely reduce passenger cabins in the stern area.

Evaluating the ice breaking capability of the DAS design reference ship with similar characteristics is used. Norilskiy Nickel is Arctic container/cargo carrier with Aker Arctic's double acting design. (The Motorship, 2008)

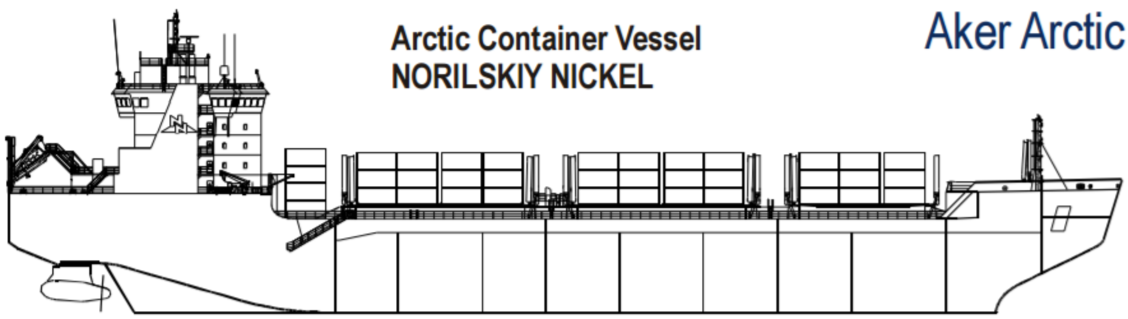


Figure 30. Norilskiy Nickel (Aker Arctic, 2006).

Norilskiy Nickel
Displacement: 61.880 tons
Length: 196 m
Beam: 23.61 m
Draught: 10.00 m winter
Speed: 15.5 knots
Speed ice thickness 1.5 m /stern first

Ships pollard pull divided by breadth gives a rough estimate of ships ice breaking capability. In order to estimate the concept ships stern ahead ice breaking capability the pollard pull of the Norislkiy Nickel must be estimated. Pollard pull can be estimated with equation (3). Reference ship has 13 MW single Azipod unit with 5.6 diameter propeller giving an pollard pull estimate of 139 t which gives 5.88 t/m when divided by breadth. Depending on optimization of case ships propeller, the pollard pull is varying. In order to proceed in 1.4 m level ice stern first, 200 t pollard pull is required. This gives 5.6 t/m which is close to Norilsk Nickel value, and she is capable of breaking 1.5 m level ice stern first with a speed of 2 knots.

3.5 Propulsion and machinery

The special requirements of propulsion for ice-going ships come from the high resistance in ice and ice interaction of propellers. High thrust/power is an important feature when considering ice breaking capability. Because high speed operations in open water, cruise ships have naturally high propulsion power. Modern cruise ships use diesel electric engines as a source of power for propulsion and for ship's systems. If the ship is equipped with fixed pitch propeller (FPP) the RPM of gensets can be adjusted based on the system load for minimum fuel consumption. Diesel electric system is convenient for ice breaking because diesel electric propulsion has high torque also with low shaft revolutions. Combined with azimuth thrusters, good maneuverability and ice management characteristics are achieved. Drawback of the propulsion system designed for ice conditions is that propeller has lower efficiency because of the ice strengthening and optimization for ice conditions. Propulsion efficiency is also reduced because of a larger clearance, propeller hub and the sensitivity of the propeller diameter to ice torque/ice loads result often in lower diameter propellers than those designed for open water. (Riska, 2010)

Conventional shaft lines with propellers and rudders have been traditionally used in ice conditions with appropriate ice strengthening. Azimuth thrusters with RPM controlled fixed pitch propellers (FPP) used in high speed operations forms optimization issue between bollard pull and speed. If high open water speed with good propeller efficiency is wanted, the bollard pull decreases and vice versa. With the use of conventional shaft line propulsion with controllable pitch propeller (CPP) and RPM control both high bollard pull and open water speed can be attained. Drawbacks of the CPP are that they have bigger propeller hub reducing efficiency and they are more expensive than FPP and not as robust. (Matusiak, 2010)

The concept case ships are equipped with ABB Azipod units, because DAS cannot use shaft line propulsion system. Depending on required icebreaking performance the propeller design is an optimization issue between the open water operation speed and the pollard thrust. If the ship has icebreaking bow the according to Equation 5 Azipod unit must have pollard thrust of 130 [kN] each in order to break required 1.4 meter level ice, which means reduced performance in open water. However using the DAS design pollard thrust can be reduced to 100 [kN] each. This means that higher efficiency in open water conditions are achieved and lower fuel consumption.

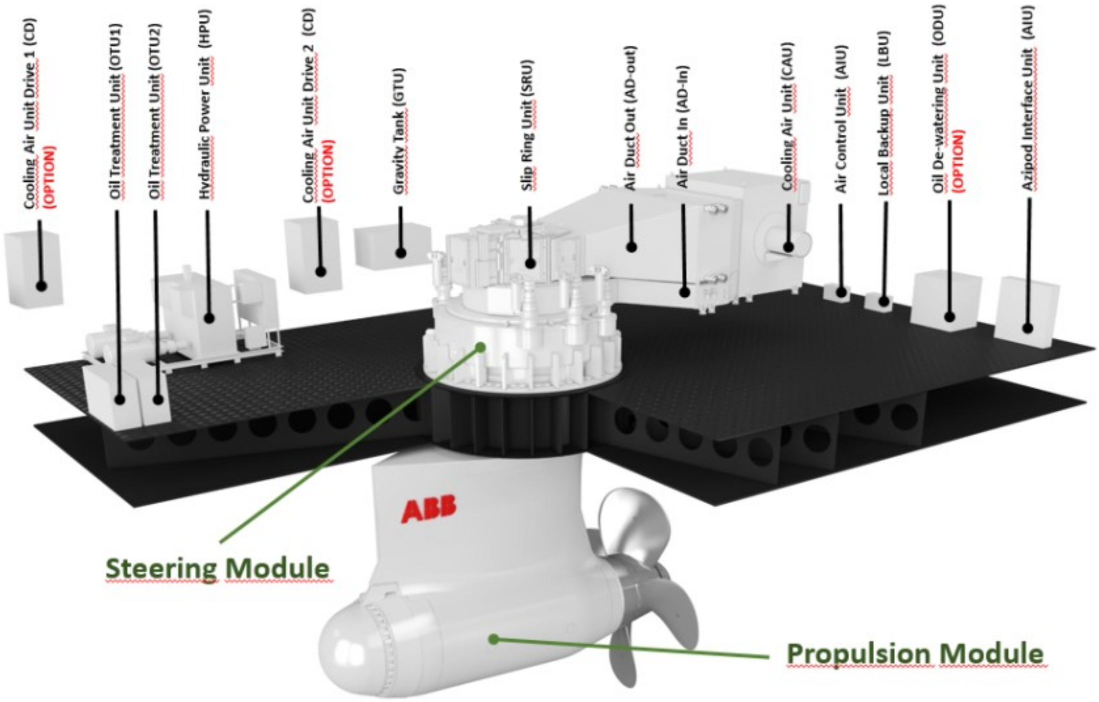


Figure 31. Layout example for the Azipod modules, units and possible optional units.

The Figure 31 shows an example for the Azipod module layout. With the use of Azipods the concept ship doesn't require stern thrusters and rudders, making the design simpler with less moving parts. Ship concept ice strengthened Azipod units are compared to Azipod units designed for open water conditions in order to see reduction in efficiency. Expertise from ABB side was sought in order to determine sufficient Azipod units in each cases. In the comparison every unit has same maximum power, but there are significant differences in the propeller designs depending on the operational speed and the pollard thrust. The version designed for ice conditions has higher torque than the open water version, which is achieved by a more sizable electric motor. Due to this the unit itself is larger and more expensive than open water unit. The ice strengthening of the Azipod units is adequate all the way to Polar Class 2, meaning that it can handle MYI. This is an important parameter for safety aspect, which reduce risk for ship to lose propulsion in case of collision with heavy ice conditions. It is vital for ship's safety to maintain functional propulsion in ice infested waters. The performance of each concept is presented in the Table 18. Ice breaking bow design has estimated to have 10 % more resistance due to lack of bulbous bow (Esa, 2015). The interaction between the ship's hull and propeller has not been taken into account in this comparison.

Table 18. Azipod unit's comparison.

Parameters	Open Water Ship	Ice Breaking Bow	DAS
Design Speed	21.3 kn	21.3 kn	21.3 kn
Effective Power	15 MW	16,5 MW	15 MW
Power Delivered 21.3 kn	2 x 10.5 MW	2 x 13.5 MW	2 x 11.5 MW
Max Propulsion Power	2x14 MW	2x14 MW	2 x 14 MW
Bollard Pull (BP)	2x 1440 kN	2 x 1300 kN	2 x 990 kN
Propulsion Power at Maximum BP	-	2 x 12,5 MW	2 x 9.7 MW
Propulsion Efficiency	0.70	0.61	0.65
Weight	2 x 258 t	2 x 416 t	2 x 416 t
Cost	2 x 11.2 M€	2 x 21 M€	2 x 21 M€

There are no special requirements in Polar Class regarding to machinery. When operating in the Arctic, pollution must be minimized because of sensitive environment and passengers onboard with awareness of the situation. In order to meet these demands possibility to use liquefied natural gas (LNG) as a main fuel of the case ship must be investigated. Significant environmental benefits can be achieved with the use of LNG including elimination of SO_x emissions, substantial reduction of NO_x and a small reduction in greenhouse gas (GHG) emissions. The US and Canada are proposing HFO Arctic reduction plan at the IMO's summer meeting 2017. This plan is includes working together with Arctic nations and there are many shareholders preparing the plan like US Coast Guard, Indigenous communities, the State of Alaska and Transport Canada. The baseline is to protect the Arctic from the future risks of shipping and offshore oil and gas industry. (The Motorship, 2016) These signs support the use of LNG as a main fuel of the ship. ABB Azipod propulsion units have already proven to work with LNG fuel in ice conditions. The new Finnish icebreaker Polaris has ABB's electric power plant and Azipod propulsion units with capability to run using LNG as a fuel, making her to comply with the IMO Tier III emission standards and special requirements for sulfur emission in the Baltic Sea. She is also able to use low sulfur diesel oil as a fuel (Arctech, 2016).

3.6 Weight estimation

Cruise ships have low DW/Δ ratio meaning that they are highly weight critical. Unexpected weight increase may kill the whole project. (Ilus, 1998) The concept cruise ship's weight will increase due to ice strengthening, Azipod propulsion units, insulation against cold climate and additional stern bridge.

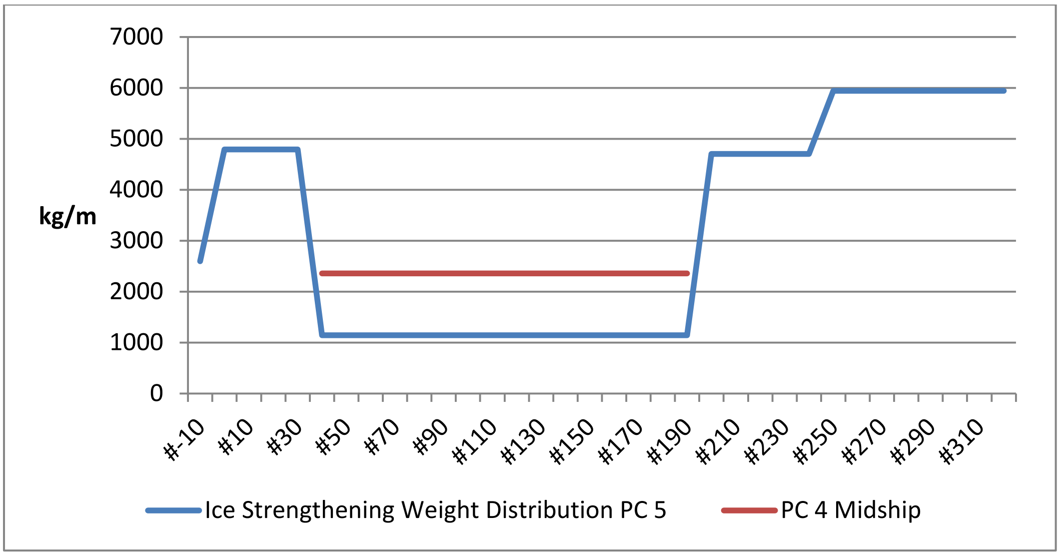


Figure 32. Weight distribution of the ice strengthening.

The Figure 32 shows the weight distribution of the ice strengthening. It can be noticed that the heaviest areas are in the bow and aft parts where the ice loads are also highest. The figure also shows that the PC 4 midship area weights 2358 kg/m and PC 5 1142 kg/m. This means that the PC 4 ship would be burdened by heavy steel weight and it would be difficult to make it economically feasible option. The center of gravity of the ice strengthened hull is calculated to be in the frame #164 with the total weight of 886 metric tons (see Appendix 5). Table 19 shows the additional weights of ice strengthened Azipods and hull with their effect to draft.

Table 19. Weight and draft of the concept ship.

Draft	8.05 m
Additional steel weight	886 t
Azipods weight	832t
New Draft	8.25 m

3.7 Fuel type and consumption

In order to operate with LNG powered vessel, LNG bunkering infrastructure must be mapped in the operational area. The Figure 33 shows that the LNG bunkering infrastructure is currently concentrated in northwest Europe. However there are several ports under development in North America, which are mostly concentrating in the southeast and Great Lakes, but also in the Pacific Northwest. (SEA\LNG, 2017)

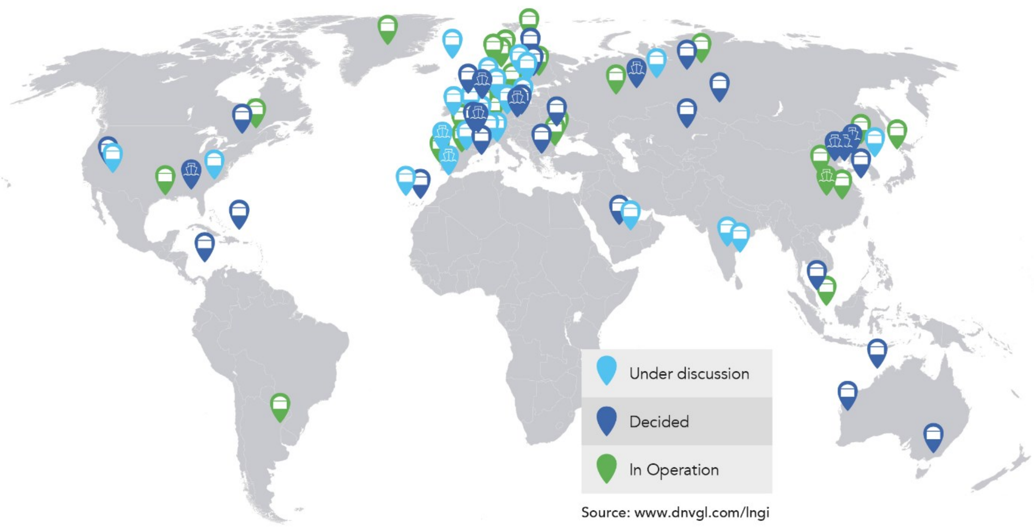


Figure 33. Global infrastructure for LNG bunkering (SEA\LNG, 2017).

While waiting for LNG infrastructure develop, ship can operate using low sulfur diesel oil which is required by Canadian authority (Transport Canada, 2009a). Ship's consumption in the normal continuous output (NCO) can be calculated with the following equation 7.

$$Q_f = q \cdot P \cdot T_V, \text{Kg} \tag{7}$$

where,

Q_f – quantity of fuel [Kg]
T_V – duration of voyage [h]
q – specific engine fuel consumption [Kg/kWh]
P – propulsion power [kW] (NCO)

When the quantity of fuel is known ship range can be now calculated with following equation 8.

$$R = \frac{Q_F \cdot 10^3 \cdot S}{P \cdot q}, \text{miles} \tag{8}$$

Q_f – quantity of fuel [ton] taken onboard
S – speed [miles/h]
q – specific engine fuel consumption [Kg/kWh]
P – propulsion power [kW] (NCO)

MS 5 is equipped with the following engines and the operating speed is achieved by 80% of the maximum continuous output (MCO):

177.4 g /kWh for Wärtsilä 12V46F 85% MCR, max continuous power 14 400 kW
180.2 g/kWh for Wärtsilä 8L46F 85% MCR, max continuous power 9600 kW

In order to use LNG as a main fuel these engines must be replaced and below is suggested possible solution:

2 x Wärtsilä 16B50DF tri-fuel engine giving 15 050 kW
2 x Wärtsilä 9L50DF tri-fuel engine giving 8470 kW

The Table 20 illustrates the fuel capacity between MS 5 and the case ships to achieve 5000 nautical miles endurance. The ASPPR requires that the ship must have sufficient fuel and water on board to complete their intended voyage in the Zones. The ship concept has ability to make its own fresh water like MS5, but the fuel capacity required must be studied. The autonomy in trial conditions is calculated using a speed of 21.3 knots which is the normal operation speed of MS 5 with the 80% of the MCO. Hotel load of a MS 5 is around 4000 kW both in harbor and at sea (Korhonen, 2016).

Table 20. Fuel capacity requirement to achieve 5000 nautical miles autonomy in open water conditions.

Ship Type	**MS 5**	**Open Water Ship**		**Ice Breaking Bow**		**DAS**	
Fuel Type	MDO	LNG	MDO	LNG	MDO	LNG	MDO
Fuel consumption: Prop./Hotel [kg/kWh]	0.187/ 0.198	0.137/ 0.152	0.187/ 0.198	0.137/ 0.152	0.187/ 0.198	0.137/ 0.152	0.187/ 0.198
Hotel Load [MW]	4	4		4		4	
Propulsion Power [MW] (21,3 knots)	2 x 11.2	2 x 10.5		2 x 13.5		2 x 11.5	
Time in hours	235	235		235		235	
Volume of the tanks [m^3]	1330	1759	1231	2174	1523	1898	1328
Weight – [t]	1197	818	1108	1011	1371	882	1196

3.8 Safety

Remoteness, lack of infrastructure, unpredictable weather, low temperatures and hazardous ice form a considerable safety challenge for cruise ship operating in the Arctic. There haven’t been as big cruise ship operating in the Northwest Passage ever and higher passenger number means higher risks. The following chapter details how to reduce risks by mitigating consequences of accidents and lowering the probability of unwanted events when operating in the Arctic conditions. The Figure 34 shows Type D bulk carrier, which was damaged in Hudson Strait.

Figure 34. Bulk carrier damaged by ice (CIS, 2017).

3.8.1 Lifesaving equipment

Lifesaving equipment of the concept ship is based on MS 5 and modified to comply with requirements of Polar Code. Currently there are life-saving appliances provided for 3820 persons on board:

- Twelve (12) life boats of partially enclosed type, each for 150 persons.
- Four (4) combined tender/life boats, each for. 267 persons in lifeboat use.
- Two (2) rescue boats, each for 6 persons. The rescue boats are not included in the LSA-capacity.
- Two (2) MES stations.

Life boats fulfill the Polar Code requirement (I-A. 8.3.3.3.1) that "no lifeboat shall be of any other than partially or totally enclosed type". Also lifeboats must provide appropriate survival resources (I-A 8.3.3.3.2), "which address both individual (personal survival equipment) and shared (group survival equipment) needs." Purpose of this equipment is to provide adequate protection against cold. In the thesis of Ihalainen, 2017 heating evaluation of lifeboat for 150 persons in outside temperatures of -5 °C, -10 °C and -15 °C. The study showed that if there are more than 90 persons inside the lifeboat, there is no need for additional heater. The thesis suggests recommendation for personal survival equipment (PSE) for cruise ships, which is lightweight and doesn't require lots of space. This consist of thermal protection aid, gloves, hat, socks, skin protection cream, sunglasses, water bottle and a small bag. (Ihalainen, 2017) With the current time window of operation this PSE would be sufficient for the concept ship. Polar Code requires survival crafts to be fully functional for the maximum expected rescue time, which can be several days in the isolated NWP.

Additionally Polar Code requires that the lifeboats and rescue boats are equipped with adequate communication devices by one each as follows:

1. *or distress alerting, carry one device for transmitting ship to shore alerts;*

2. *in order to be located, carry one device for transmitting signals for location; and*

3. *for on-scene communications, carry one device for transmitting and receiving on-scene communications.*

Also, the lifesaving equipment should be fully functional at the PST. According to Polar Code all the persons on board must be provided with insulated immersion suit or a thermal protective aid. (IMO, 2015) This means that there must be immersion suits for 3820 persons.

3.8.2 Ice detection

Polar Class 5 gives a special opportunity to the case ship to operate in thick first-year ice conditions which can also include old ice. Still the ice detection is really important since the hull is not designed to encounter multi-year ice conditions like ice bergs. Larger detectable ice bergs don't form as big threat as the smaller ones which are called bergy bits and growlers. These can be hard to detect between waves because their height above sea surface can be from less than 1 meter to 5 meters and weight is between one and 10 tons. (Paaske *et al.*, 2014)

Ice detection is made using electronic aids such as radar and combined with visual observation. Forward looking sonar is important piece of equipment providing underwater picture even in harsh and dark weather conditions. It can be used to detect shallow areas and most importantly icebergs which typically have most part hidden underwater.

The case ship will be also equipped with ice searchlights, ice radar and a thermal imaging system. It will also have navigation system which can display near real-time satellite ice imagery and ice forecasts. Also ice navigator is required on board who has experience operating in Arctic conditions and who has power to be in charge of the deck watch and is able to make maneuvers to avoid concentrations of ice that might have endangered the ship. (Government of Canada, 2017)

3.8.3 Icing and winterization

Winterization ensures that the vessel is capable of and suitably prepared for operations in cold climates. Winterization is based on design temperature. Cruise ship operations take place usually during night when also the temperature drops down. When operating temperature above zero in the NWP the seawater spray can freeze immediately when in contact with the vessel. This means that the ice accretion is likely to occur and the ship must include ice accumulation in intact stability conditions.

1. 30 kg/m2 on exposed weather decks and gangways;

2. 7.5 kg/m2 for the projected lateral area of each side of the ship above the water plane; and

3. the projected lateral area of discontinuous surfaces of rail, sundry booms, spars (except masts) and rigging of ships having no sails and the projected lateral area

of other small objects shall be computed by increasing the total projected area of continuous surfaces by 5% and the static moments of this area by 10%.

Icing should be monitored onboard to ensure that ice accretion does not exceed the allowance limit. (IMO, 2015)

Icing allowance included in the stability calculations should be included in the PWOM. According to Polar Code the ship should be designed to be such that it minimizes the accretion of ice. This is a passive method used to minimize icing. However there must be also active winterization which prevent icing or de-ice occurred icing. De-icing can be done manually by using tools such as axes or wooden clubs for removing ice from thorough the ship. Also heating is generally used method to protect the ship's functions and equipment from icing. Disadvantage of this method is increased energy consumption. (Ihalainen, 2017)

Winterization is not considered in detail in the concept phase. For cruise ships it is important to keep the escape routes and life-saving appliances ice free. The Polar Code requires that the ice accretion must be removed from spaces related to water and weathertight integrity, machinery, navigation, life-saving appliances, arrangements and fire safety. Even though it is not required in Polar Code, it would be important that the cruise ship would have total ice free protection in critical areas such as embarkation decks, staircases and escape routes.

3.8.4 Damage stability

Operation in ice conditions forms a higher threat for damage than in open water conditions. Even though the ship has sufficient ice strengthening there is a still possibility to experience damage event due to ice. In the study by Kubat and Timco 125 damage events were analyzed which has taken place in Canadian Arctic between 1978 - 2003. The study shows that 73% of the damage events occurred when there was multi-year ice present in the ice regime. Additionally the study shows that in three accident cases the vessel sank, but these vessels were classified based on AIRSS to be Type A, B and E vessels and they encountered MYI conditions. In the 15 accidents of CAC4 vessels, there were always MYI present, and the damage severity was in levels 2 and 3 meaning that most of the cases it was about deformation of the hull and the ship were not lost. As it was earlier explained the Polar Class 5 is something between from Type A and CAC4 vessel. It is also notable that in none of the first year ice damage events the vessel was lost. Worth of mentioning is also that there were total 19 cases where the MYI has caused a large and significant hole to the hull but the vessel survived. (Kubat *et al.*, 2016)

The polar code takes these kinds of ice related damages into account with deterministic damage scenario. In the polar code's damage stability regulation, the damage length and height dimensions are in relation to ship's dimensions meaning that on larger vessels the size of the damage increases. The Polar Codes ice damage extents are presented below (IMO, 2015):

1. The longitudinal extent is 4.5% of the upper ice waterline length if centered forward of the maximum breadth on the upper ice waterline, and 1.5% of upper ice

waterline length otherwise, and shall be assumed at any longitudinal position along the ship's length;

2. the transverse penetration extent is 760 mm, measured normal to the shell over the full extent of the damage; and

3. the vertical extent is the lesser of 20% of the upper ice waterline draught or the longitudinal extent, and shall be assumed at any vertical position between the keel and 120% of the upper ice waterline draught.

In order to fulfill these requirements the concept ship has double side 1,28 m from the outer shell. The double side protection is illustrated with Polar Codes damage extents in the Figure 35.

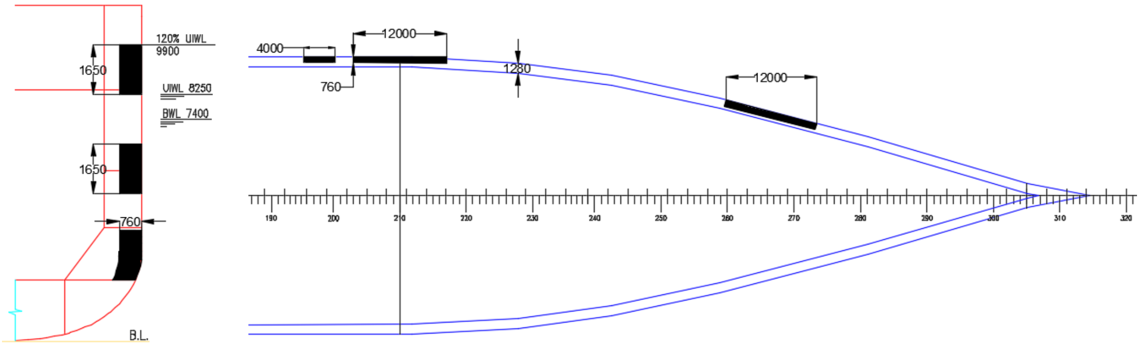


Figure 35. The ice damage extents.

The weight of the double side structures haven't been taken into account, because in new cruise ships like MS5 the ship is practically double sided.

3.9 Other equipment

The case ship will be equipped with rib boats for expeditions to take passengers to experience Polar nature. The ship can also use the tender boats to transport passengers to shore since there are no ports suitable for large cruise ship. In addition, the ship is equipped with two helicopters which can be used for emergency cases and air view excursions. The balconies of the ship could be glassed and heated to protect them from icing and giving opportunity for passengers to enjoy the Arctic views in warm conditions.

3.10 Waste disposal

Concept cruise ship naturally produces waste, when in operation including contaminated water ballast, waste oil, domestic garbage and human wastes. “These wastes must be safely and efficiently disposed of, or retained on board, until they can be discharged ashore”. (Canadian Coast Guard, 2012) Examples of oily waters are bilge water, dirty ballast water, tank washing and purifier sludge. Oily water separator is usually used to limit the oil content of bilge water to 15 parts per million (ppm), like in MS 5. However, discharging 15 ppm oil into Arctic waters contravenes the ASPPR, which has zero discharge in Arctic waters. (Albert & Danesi, 2011) This means that the bilge water must be kept in bilge water tank, and discharged when leaving Canadian waters north of 60°.

Discharge of garbage is forbidden under the ASPPR, burnable garbage is handled with incinerators and non-burnable garbage is stored on board. All the black and grey water are purified with advanced waste purification system. After purification the clear and disinfected water is discharged to on shore or to sea. The ballast water is used to compensate the consumption fuel oil and fresh water to adjust draught, trim and heel of the vessel in order to maintain favorable stability and seakeeping characteristics. However harmful aquatic organisms have been identified to spread because of shipping activities causing threats to marine ecosystems. Taking ballast water from one region and discharging it to another introduces new species in sea areas with devastating consequences. Fragile Arctic ecosystem must be protected and the ship concept is equipped with ballast water treatment plant which is capable of treating the ballast water according to IMO Resolution MEPC.174(58) and BWM-T (D-2). (IMO, 2017)

4 Economic Analysis

Economic analysis concentrates on shipyard and ship-owner aspects. Shipyard is interested of the additional building cost to convert MS 5 feasible to operate in Arctic conditions and ship-owner is also interested to know how the design effects on voyage costs. Economic analysis is made based on the investment costs and voyage costs. Operating costs, periodic maintenance costs, and capital costs are not considered since they are depending on the ship-owner, not the actual design.

4.1 Investment costs

Investment costs are based on MS5 costs with added equipment and structures. In a passenger ship the ship hull formulates 15-20% of the total cost (Ilus, 1998). The total added cost for ice strengthening is calculated based on the steel weight. In the thesis of Ilus, 1998 is shown a method to estimate the man hours required in the different hull sections based on the steel weight. It is simplified method, but it is based on Turku shipyard and is well suitable in concept design phase. The Table 21 shows the results of cost calculations of the concept ship's ice strengthening giving total of 29 M€.

Table 21. Additional cost of the ice strengthening.

Area	Weight	Steel cost (950 €/ton)	Man hours	Total	Working cost
Stern Section	205	194300 €	40h/t	8180 hours	274000 €
Midship	143	135700 €	32h/t	4570 hours	490800 €
Bow	539	511800 €	40h/t	21549 hours	1293000 €

The Table 22 shows the total costs of the ice strengthening and Azipods. The total cost of MS 5 was estimated to be roughly around 500 M€. With the added cost of 71 M€ the price of the concept is 14% higher than the Turku's Mein Schiff series ships.

Table 22. Major added costs of the concept ship.

Item:	DAS	Ice Breaking Bow
Ice strengthening	29 M€	29 M€
ABB Azipods	2 x 21 M€	2 x 21 M€
Total:	71 M€	71 M€

4.2 Voyage costs in open water conditions

The concept cruise ship has higher resistance and lower propulsion efficiency than cruise ships designed purely on open-water because of the added weight of ice strengthening in the hull and propulsion systems. Removal of bulbous bow in the other concept increases significantly ships resistance, thus fuel consumption is higher.

Voyage costs are variable costs, which includes fuel cost, port charges, canal dues and tugs. There is no fee system in the NWP and icebreaking services are also free of charge. Also there are no adequate deep-water ports throughout the NWP meaning that there are no port charges. (Eger, 2010)

Ice conditions are varying in the area considerably thus voyage costs calculations are based on such conditions in the summer, when the ice conditions can be avoided. It is worth mentioning that voyage costs in ice conditions are excluded, because ice conditions are highly variable on a temporal and spatial basis (Frederking, 2017). Algorithm that generates optimal route, taking into account variable ice conditions be needed in order to estimate voyage costs.

Table 23. Total fuel consumption of DAS in the NWP cruise.

Route legs	Distance [nm]	Average speed [knots]	Navigation time + time in port [hours]	Fuel consumption [metric tons] LNG	Fuel consumption [metric tons] MDO
Anchorage - Dutch Harbor	720	20.4	35 + 12	140	189
Dutch Harbor - Nome	790	20.4	39 + 12	153	207
Nome – Ulukhaktok	1557	20.4	76 + 12	294	398
Ulukhaktok – Cambridge Bay	570	20.4	28 + 12	112	152
Cambridge Bay – Resolute	477	20.4	23 + 12	95	129
Resolute – Bond Inlet	450	20.4	22 + 12	90	122
Bond Inlet - Ilulissat	566	20.4	28 + 12	112	151
Ilulissat - Nuuk	400	20.4	20 + 12	81	109
BUNKERING	5530	x	x	1077	1457
Nuuk - Boston	2130	20.4	104 + 12	400	541
Boston – New York	270	20.4	13	50	67
Total	**7930**		**768 hours (32 days)**	**1527 metric tons / 3284 m^3**	**2065 metric tons / 2295 m^3**
Required Fuel Capacity				**1185 metric tons/ 2549 m^3**	**1602 metric tons / 1780 m^3**

The Table 23 presents the fuel consumption of the DAS concept. Speed of the ship has reduced from 21.3 knots to 20.4 knot due to sea margin of 15%. Also 10% fuel reserve has been added to the total fuel capacity. The total voyage time is 32 days, which is almost the same as Crystal Serenitys plan complete the voyage in 31 days in year 2017. This means that Crystal Serenity is able to operate swiftly in the Narrow Channels of the NWP.

In case of the ship encounters ice conditions, the estimated fuel capacity is not adequate. Fuel reserve for ice conditions must be estimated, and it is based light ice conditions at the beginning of August 2016. Figure 36 presents the leg, where ice conditions are encountered. Concentration of ice in this leg is between 1-6, meaning that the ship is interacting both with open water and ice. The ship can also try to avoid ice interaction with maneuvers. Based on egg code, the ice consists of thick and thin FYI, meaning that thickness is varying from 30 cm to over 120 cm. The ice covered area is estimated to be approximately 200 nautical miles and level ice with thickness of 50 cm is considered to be good average of this leg.

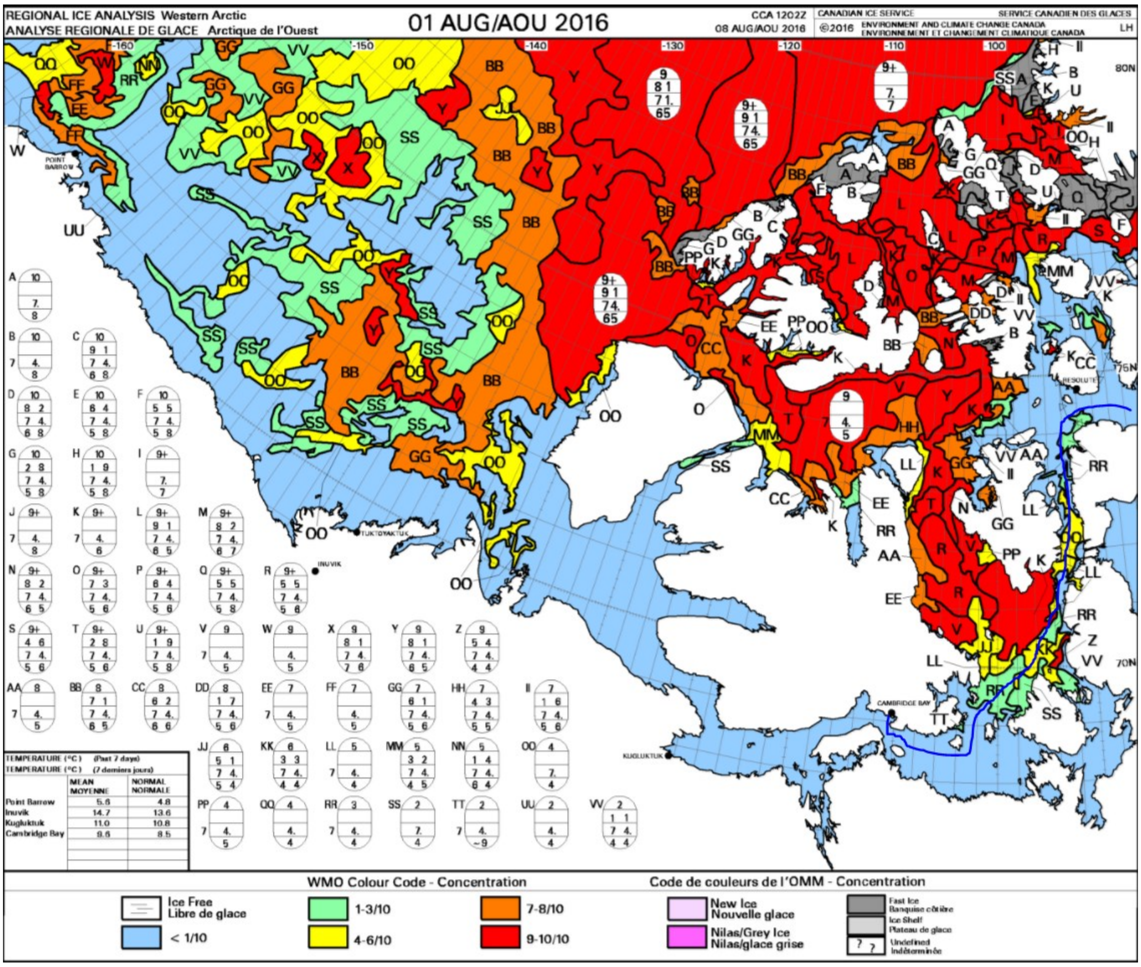


Figure 36. Leg marked with blue, which includes ice conditions.

In order to estimate the fuel consumption for this leg, the speed of the vessel in thickness of 50 cm level ice must be estimated. Because the ice conditions are not severe, the ship is operating ahead, breaking ice with bulbous bow. It can be determined from Figure 29 that the speed of the ship would be roughly 9 knots in 50 cm level ice. Power of 2 x 9.7 MW is used in Appendix 4 energy calculations, because it gives maximum value for PB in DAS concept. The Table 24 shows how much fuel reserve is required additionally for light ice conditions. Extra 100 metric tons of fuel reserve is added to cover additional fuel consumption due to ice conditions.

Table 24. Effect of ice conditions in MDO consumption.

Ship Type:	DAS	Ice Breaking Bow
Weight [metric tons]	48	64
Volume [m^3]	54	71

Further transport analysis is needed, which would take into account maneuvering and ice conditions. The ship equipped with open water Azipod units MDO consumption was 1920 metric tons and ice breaking bow concept 2356 tons. Fuel consumption can be reduced significantly with DAS concept and it is the most feasible option in this case.

4.3 Effect on the ticket price

Estimating the ticket price is problematic, because it is dependent on the cruise lines cost structure and business model. The cruise line ticket price and onboard revenues must cover the cruise line expenses and leave some margin for the profit. In the Table 25 is outlined as a percentage of total revenues and expenses of the Royal Caribbean Cruises LTD (RCCL). RCCL is used as a reference due to their long history with Turku shipyard and they also own 50 % of the TUI Cruises, which is a joint venture cruise line of the German tourist firm, TUI AG and the RCCL. TUI Cruises owns and operates Mein Schiff series.

Table 25. RCCL's results as a percentage of total revenues and expenses in 2015. (RCCL, 2015)

Passenger ticket revenues	73.0 %
Onboard and other revenues	27.0 %
Total revenues	100 %
Cruise operating expenses:	
Comissions, transportation and other	16.9 %
Onboard and other	6.7 %
Payroll and related	10.4 %
Food	5.8 %
Fuel	9.6 %
Other operating	12.1 %
Total cruise operating expenses	61.4 %
Marketing, selling and administrative expenses	13.1 %
Depreciation and amortization expenses	10.0 %
Impairment of Pullmantur related assets	5.0 %
Restructuring and related impairment charges	- %
Operating income	10.5 %
Other expense	(2.5) %
Net income	8.0 %

In order to estimate the ticket price, the total fuel cost of the voyage must be calculated. Because there is no infrastructure available for LNG use, the calculations are made with marine diesel oil. MS 5 is equipped with scrubber system, which is capable of reducing SOx emission by 97.15%, thus the ship can use fuel with sulfur content up to 3.5%. IFO380 is suitable option with max sulfur content of 3.5%. When examining the average price of IFO380 in the America, the price is varying from \$257/mt to \$360/mt in the timeline of May 2016 to May 2017 (Ship & Bunker, 2017). A rough average value would be \$300/mt. However when looking at annual report of RCCL, in the year of 2016 fuel consumption in metric tons was 1409 000 and cost was \$716 million, giving \$508/metric ton, which is much higher than \$300/mt (RCCL, 2015). There might be some added cost related to the bunkering process, which are the reason for higher price. Price of \$508/metric ton is used when estimating the ticket price and the results are shown in the Table 26. These values are over optimistic since they don't take into account higher capital costs.

Table 26. Ticket price based on fuel consumption.

Open Water Ship	DAS	Ice Breaking Bow
$2655	$2856	$3258

Based on RCCL annual report TUI Cruises received secured financing of the ships on order with Meyer Turku up to 80% of the ship price is capitalized with the loan. Amortizing of the loan is done in the period of 12 years and EURIBOR plus interest rate is 1.75 %. With the ship price of 570 M€ and using German loan re-payment system with the 80% of the ship price (see Figure 37), leaving 114 M€ funded by bank facility.

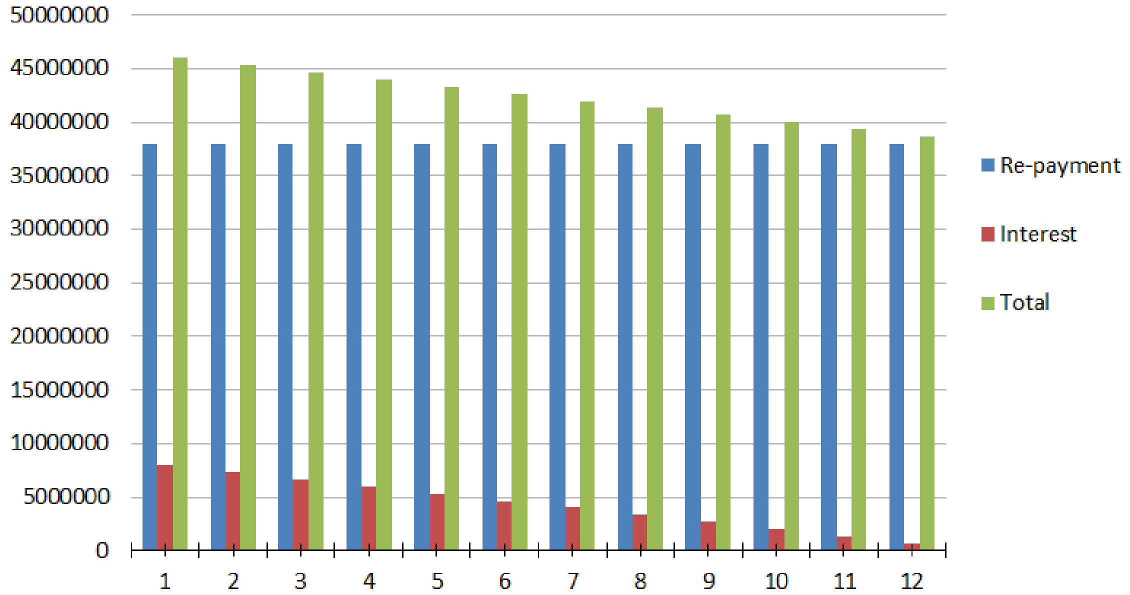


Figure 37. German loan re-payment system for ship concept.

Total cost of the ship in the period of 12 years is 622 M€ including interest expenses. If the operation time of the ship is expected to be 30 years and based on RCCL's depreciation and amortizing expenses of 10 %, the ticket price of the concept cruise ship for the one day cruise is 148 €. With this value the total ticket price for 31 day long NWP cruise would be 4600 € giving profit approximately 8%. However this consideration doesn't take into account higher fuel consumption and ice conditions. Crystal Serenity's ticket prices for the cruise in 2017 are starting from 19500 €. If the concept ship would be able to ask as high ticket prices, the business prospects would be really encouraging.

5 Conclusions

Meyer Turku shipyard order book is looking better than ever in the shipyard's history and overall cruise ship business is booming. Cruise lines are seeking new ways to attract customers with new exotic destinations including Arctic and Antarctica. The goal of this thesis was to find design solutions for existing Meyer Turku ship design, to be able to operate in the Northwest Passage providing good level of safety and economically feasible option for ship-owner. With the challenging conditions of the NWP the concept ship is suitable to operate in other sea areas like in the Antarctic. With the double acting design the ship can be used also in more traditional cruise lining, because of good open water performance. Overall the goals of the work were achieved making the concept feasible to operate in the Arctic. Of course in the concept phase design is not accurate and detailed, but to find main characteristics and requirements which must be fulfilled in later design phases. The ship concepts general characteristics are detailed below in the Table 27.

Table 27. Final characteristics of the concept designed for the NWP.

Length over all	295 m
Length between perpendiculars	273 m
Breadth, moulded	36 m
Draught, moulded max	8.25 m
Ice class	PC 5
Propulsion power	2 x 14 MW Azipod units
Maximum PB	2 x 990 kN
Main machinery power	48 000 kW
Speed	21.3 kn
Range	5530 nm
Ice breaking capability (stern first)	1.4 m level ice
Operation area	Worldwide
Operation time	From June to mid-September in NWP
Additional weight of ice strengthening	886 metric tonnes
Additional weight of Azipods	832 metric tonnes
Fuel Oil	1700 metric tonnes

5.1 Evaluation of the concept

The most important parameter of the concept was to ensure safety for passengers. Biggest safety factor when operating in ice conditions is adequate ice class. Comprehensive analysis for choosing the correct Polar Class was one of the main objectives which has huge impact for the cost and weight of the ship. Studied ice conditions and POLARIS risk assessment tool the suitable ice class founded to be Polar Class 5. At the beginning Polar Class 4 was estimated to be sufficient, but study revealed that lower class of PC 5 was adequate, which leads to lower weight, investment cost and operational costs. Structure modifications of the MS 5 were made to meet the requirements concerning Polar Class 5. These modifications increased steel weight of the ship radically, which has effect on ships draft even though the extra high strength steel with yield strength of 500 MPa was used whenever possible. There might be possibility to reduce steel weight, because weight optimization hasn't been done in the concept phase. On the contrary the insulation weight, stern bridge and other equipment were not taken into account in weight estimation. Accident data was also studied, which revealed that MYI has caused most of the accident cases in the area. In case of ice damage, the ship is protected with double side which also fulfills Polar Codes damage stability requirements.

Selecting suitable propulsion system for the ship concept was crucial, because it has big impact of the economics of the ship, general arrangement and safety. ABB Azipod's good track record with the ice breaking ships made the selection easy, giving energy efficient, compact and safe solution for the concept. ABB was more than happy to help to provide information about their products. They also did CFD calculations and propeller optimization, based pollard bull and open water speed requirements which were set on each concept options.

Operation window of the ship was selected to be from the beginning of June to the mid-September, giving total of 3.5 months season in the NWP. Operation of the ship was considered to be independent without icebreaker escort. Ice conditions and air temperatures are highly variable, which are affecting the length of the season. Even though the ship could withstand the ice conditions at the beginning of June it is most likely not economically feasible to start the operations. Slow speed in severe ice conditions would excess the patience of passengers and fuel reserve. Optimum operation conditions for the ship would be open water with some ice conditions. Some ice breaking operations wouldn't effect too much on the fuel consumption and operation time, but would be a memorable experience for the passengers. During the off-season the ship could possibly transit to the Antarctic where is a market opportunities for this kind of cruise ship. The ship has adequate ice class to operate whole Antarctic summer season which starts at late October and lasts in the middle of March. This would mean that the ship has more than one and a half month to transit in to the Antarctic waters after the NWP operations, which are planned to stop in mid-September. After the austral summer season in Antarctic, there would be two and a half months to transit back to NWP. With these operation seasons the ship wouldn't need to apply PST requirements. During transits the ship could also transport passengers, but the ticket price would be probably lower than in Arctic and Antarctic.

With the estimated ticket price of 148 €/day it is assumed that the ship is operating year-round without breaks in operations. The ticket price is really low when comparing for smaller cruise ships operating in Arctic and Antarctic, and there would be margin to increase the ticket price, but still maintain it under average prices. This is due the economies of scale, since other operators have significantly smaller vessels. Also vessels operating in the Arctic and Antarctic are generally old meaning that their energy efficiency is much lower than the ship concept's.

One drawback of the concept was the lack of LNG infrastructure in the North America. LNG as a main fuel is not only economically feasible option, but it would give the cruise ship green label, and probably boost the brand of the concept in the eyes of the ship-owner and passengers.

5.2 Discussion and future considerations

Tool for estimating the fuel consumption in NWP, which would also take into account present ice conditions, is a must when considering business opportunities with this kind of ship concept. The ice conditions have significant impact to the duration of the cruise, fuel consumption and also comfort of passengers. In the later phases, the noise and vibrations caused by interaction of the hull/propulsion and ice could be analyzed. There are strict restrictions in the cruise ship regarding noise and vibrations meaning that ice interaction could form a serious problem. Possible solutions such as additional acoustic insulations, sound-absorbing materials and structure modifications should be studied.

Study of using transversal framing system in the hull areas and FEM analysis of structures should be performed in the following rounds of design. With this kind of optimization of structures the concept steel weight could be reduced. Study of most profitable operation profile balancing between customer expectations and voyage costs should be attained. If the operational profile of the ship is going to change for easier ice conditions, where Polar Class 6 ice class could be used, the ship could have bulbous bow, without double acting design. This would lead to significantly lower weight and voyage cost. Also with this kind of design traditional propeller shaft line propulsion could be used with controllable pitch propellers, without the need to balance between the pollard bull and open water performance. Different route possibilities and additional use of the ship is important research topic for the future. There might be possibility to even to operate the ship in the North Pole, if predictions for ice free Arctic actualized before the year 2050 (Notz & Stroeve, 2016).

Comprehensive study about future views of recreational shipping in Polar areas should be conducted. For example SWOT-analysis of cruise business in the Arctic and Antarctic, before this kind of purpose built vessels are built. If the cruise market for one reason or other goes done in these regions, the ship with high ice strengthening and expensive equipment required for Polar operations would burden the ship’s profitability drastically.

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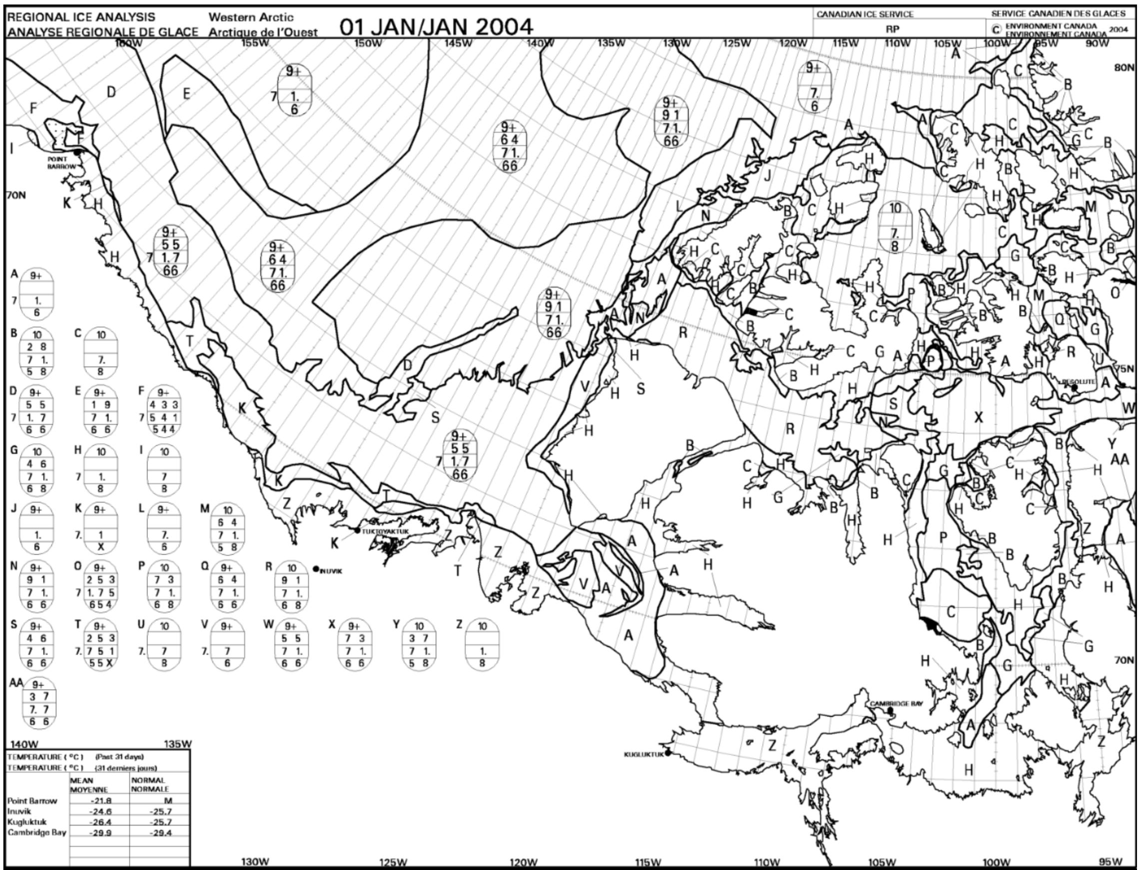
List of appendices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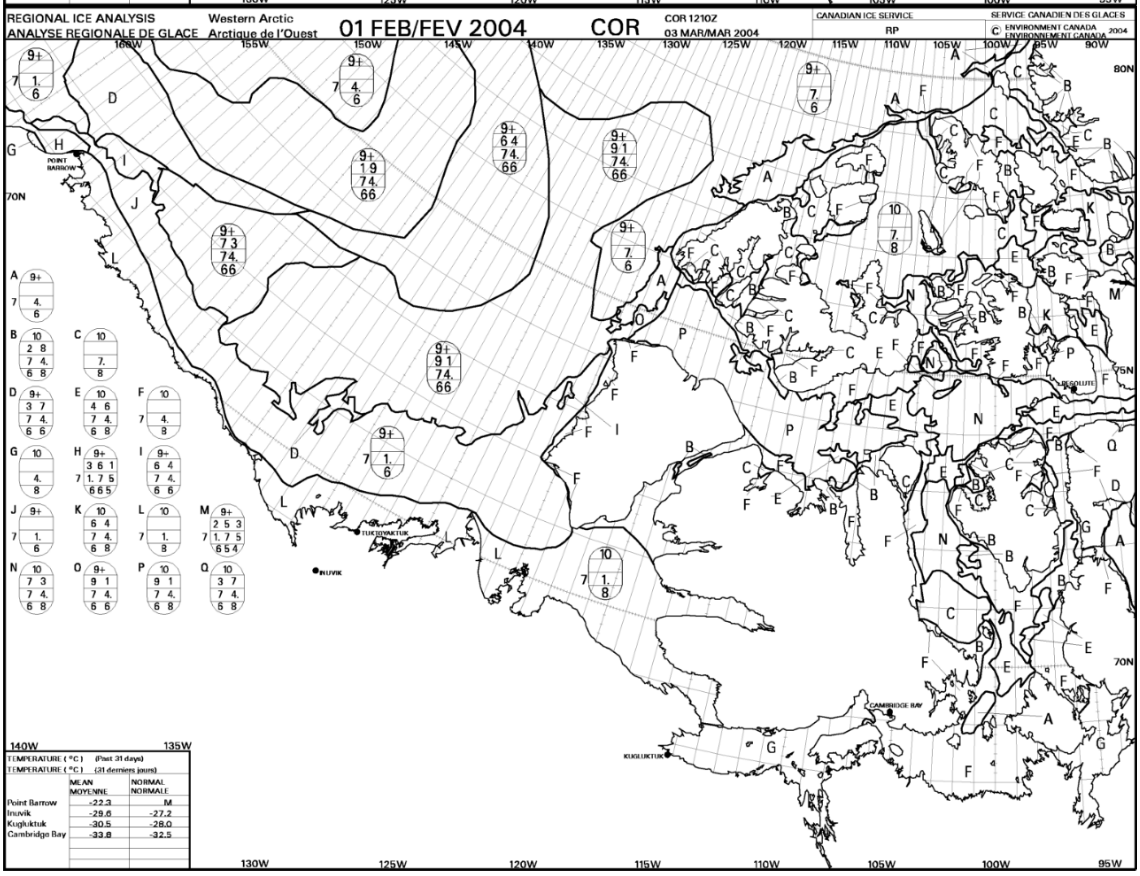
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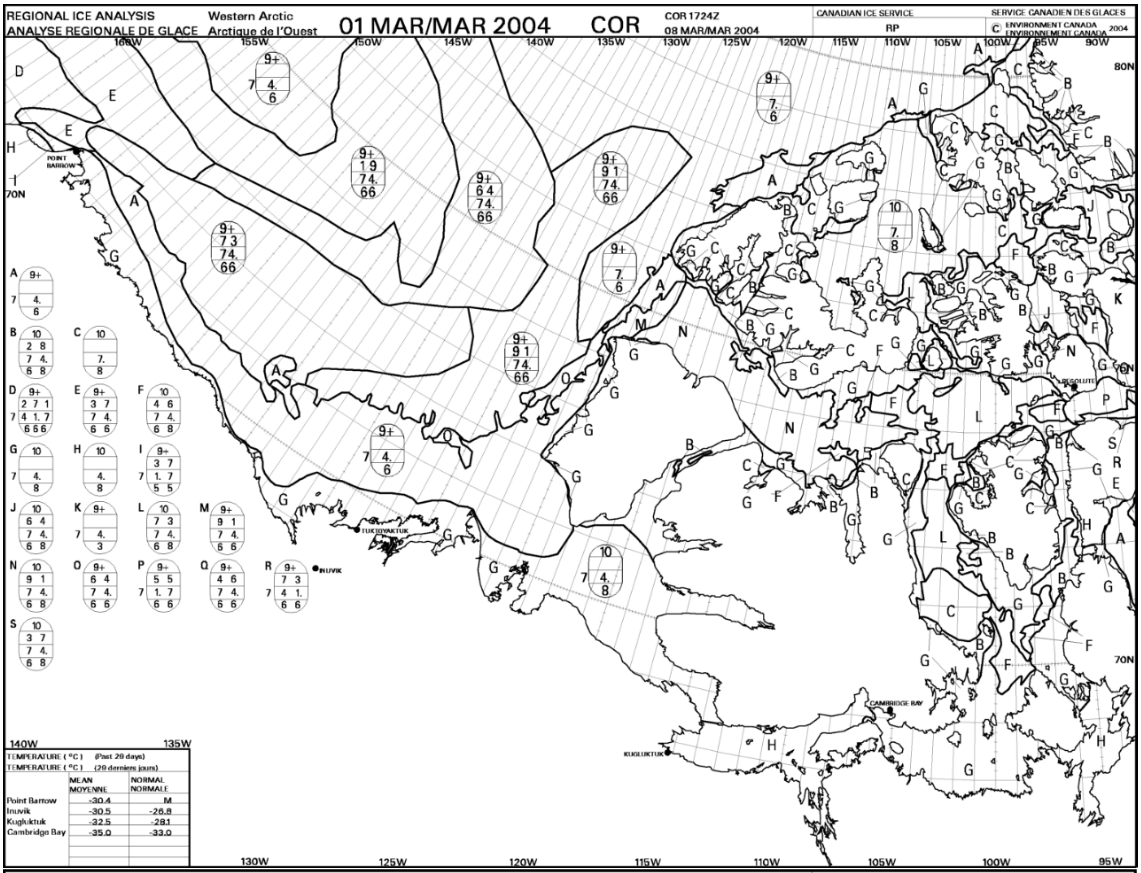
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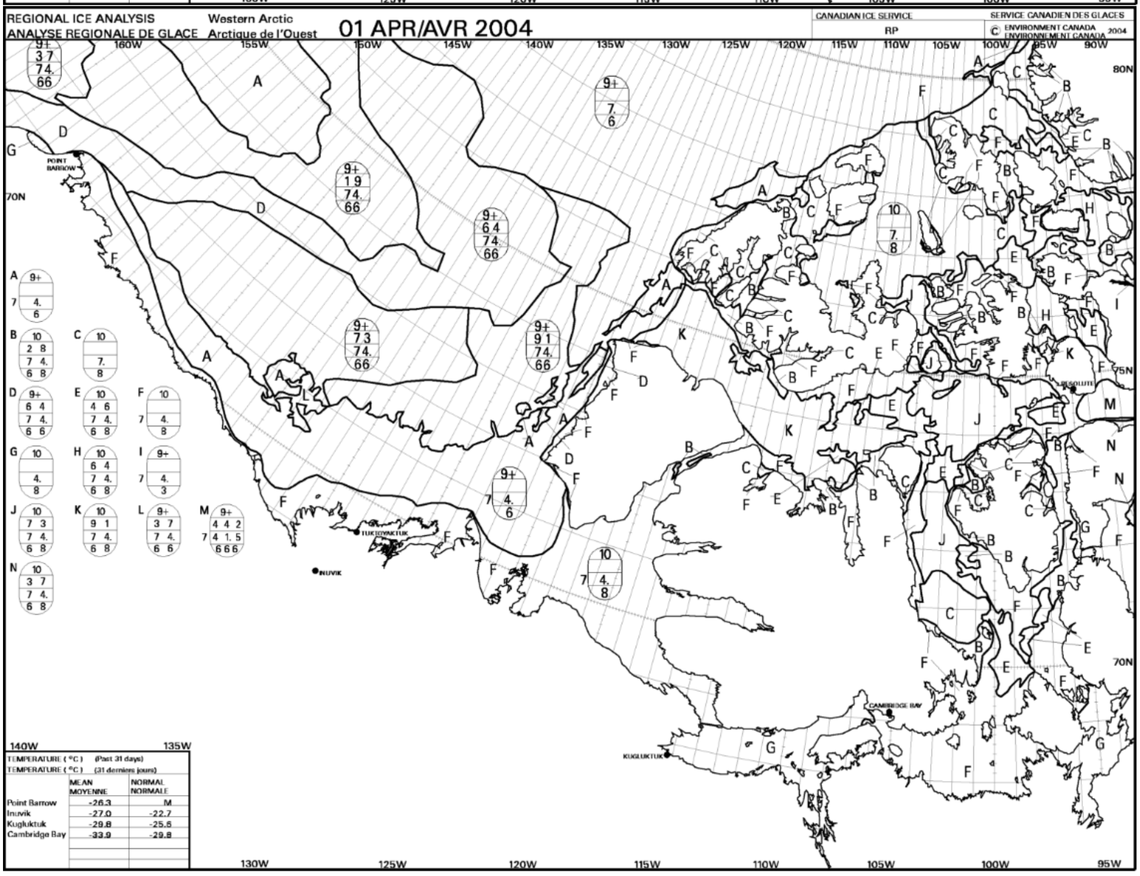
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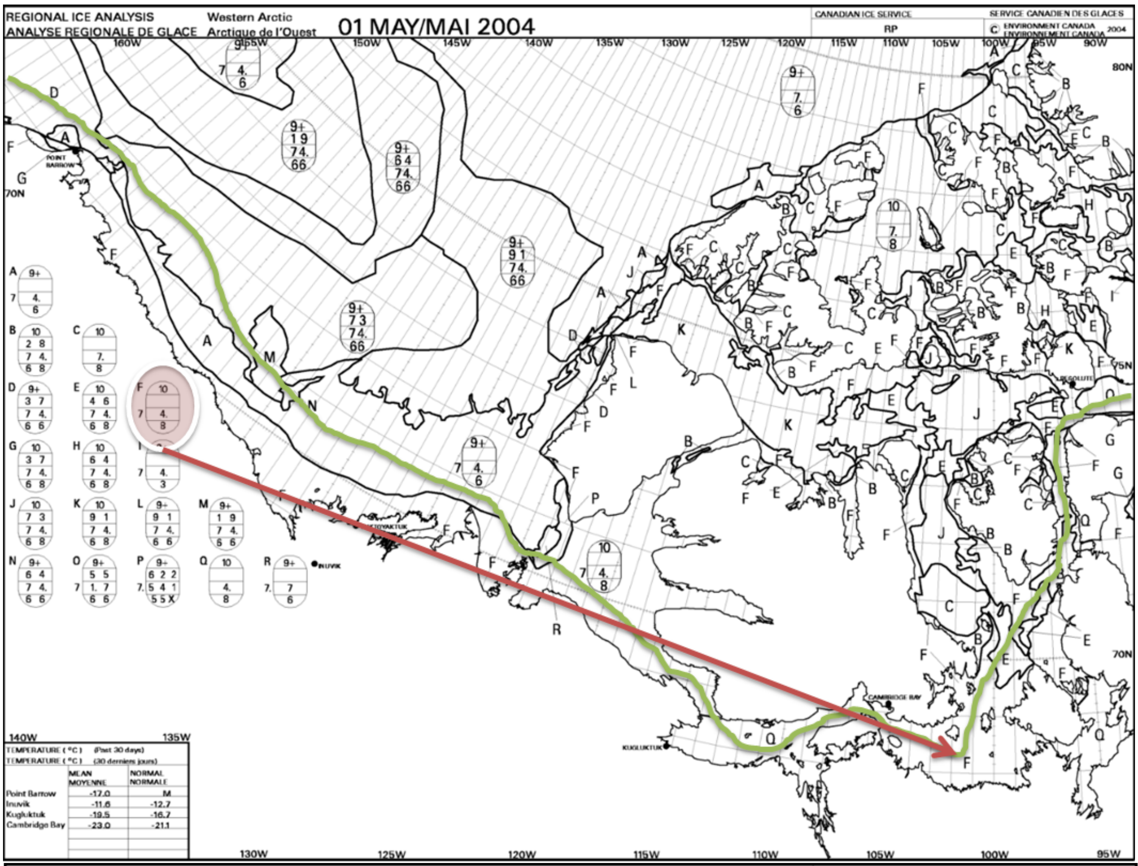
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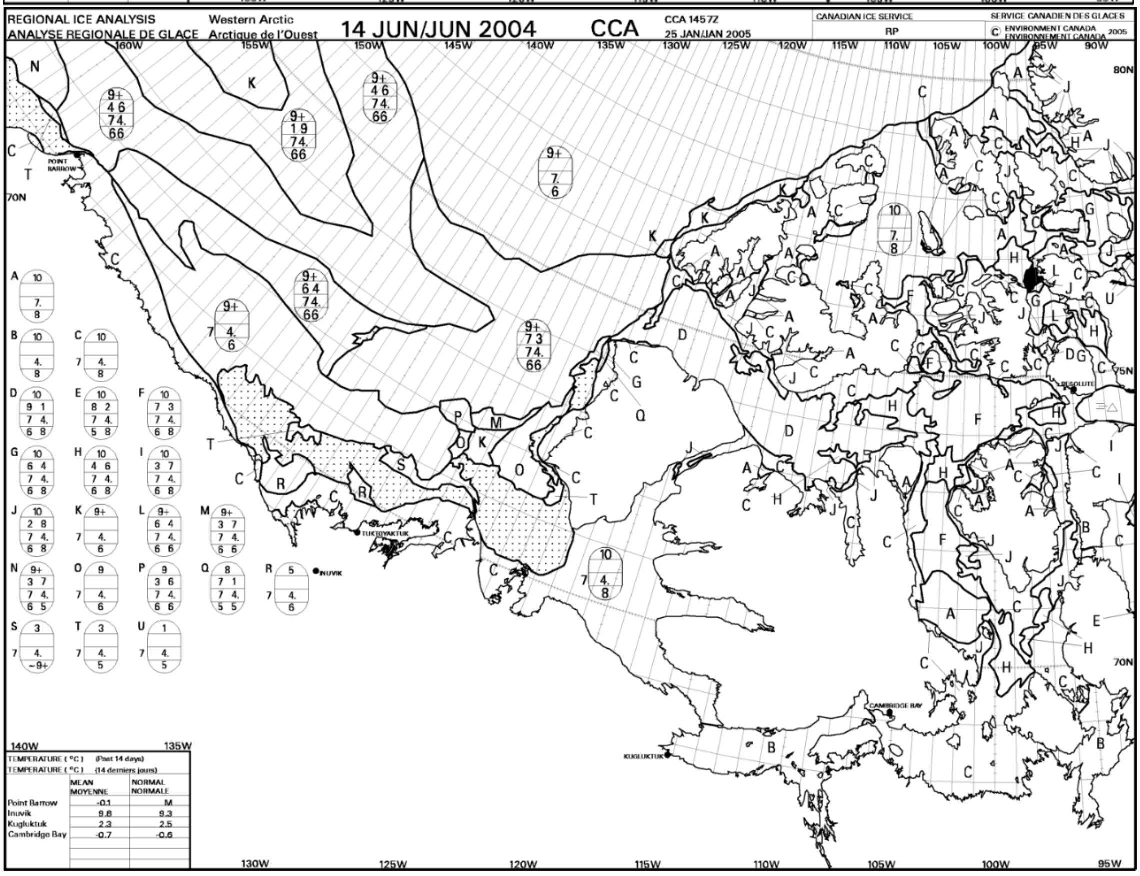
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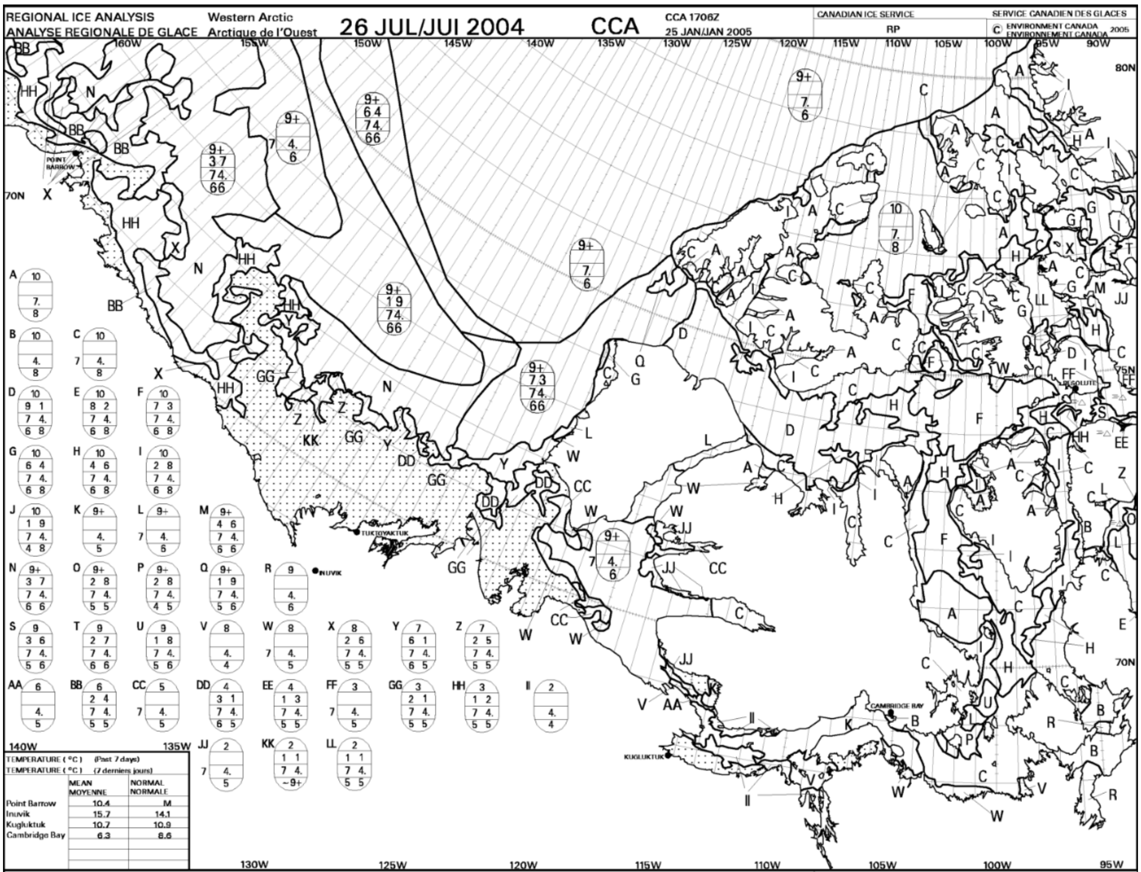
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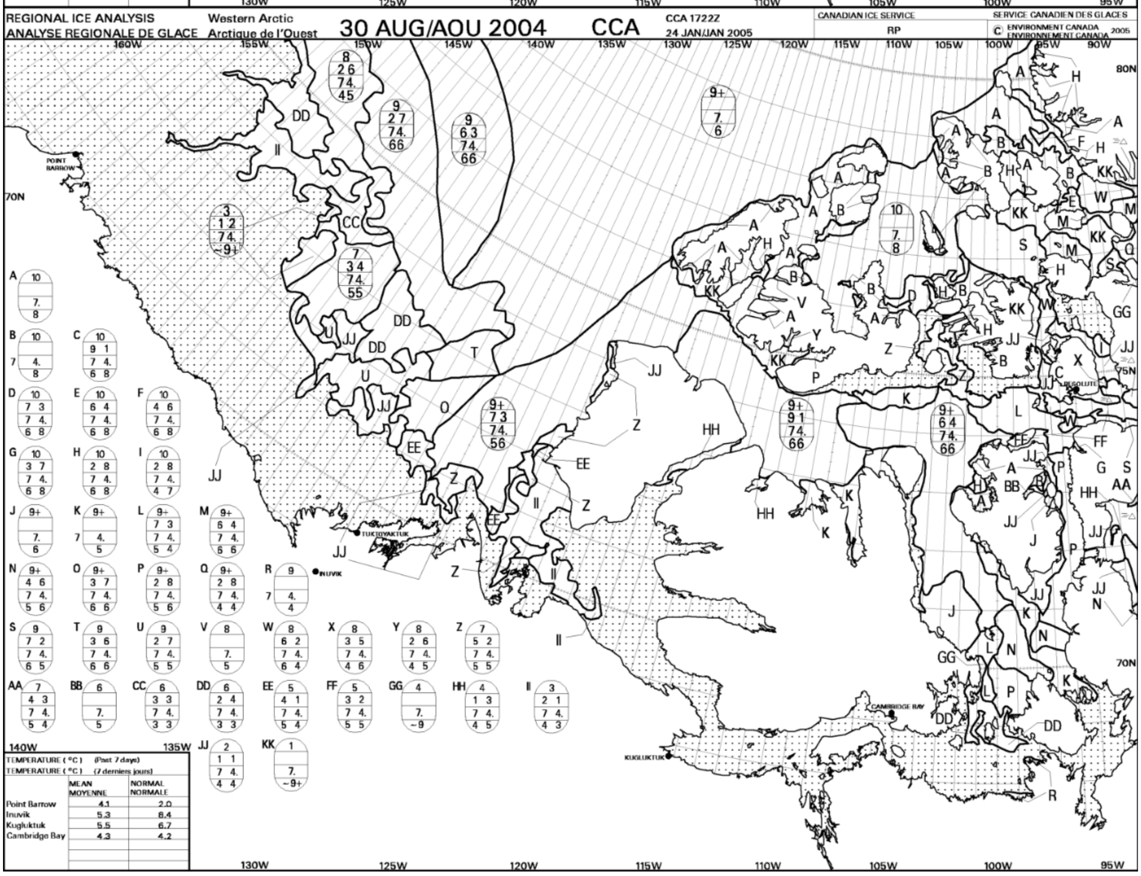
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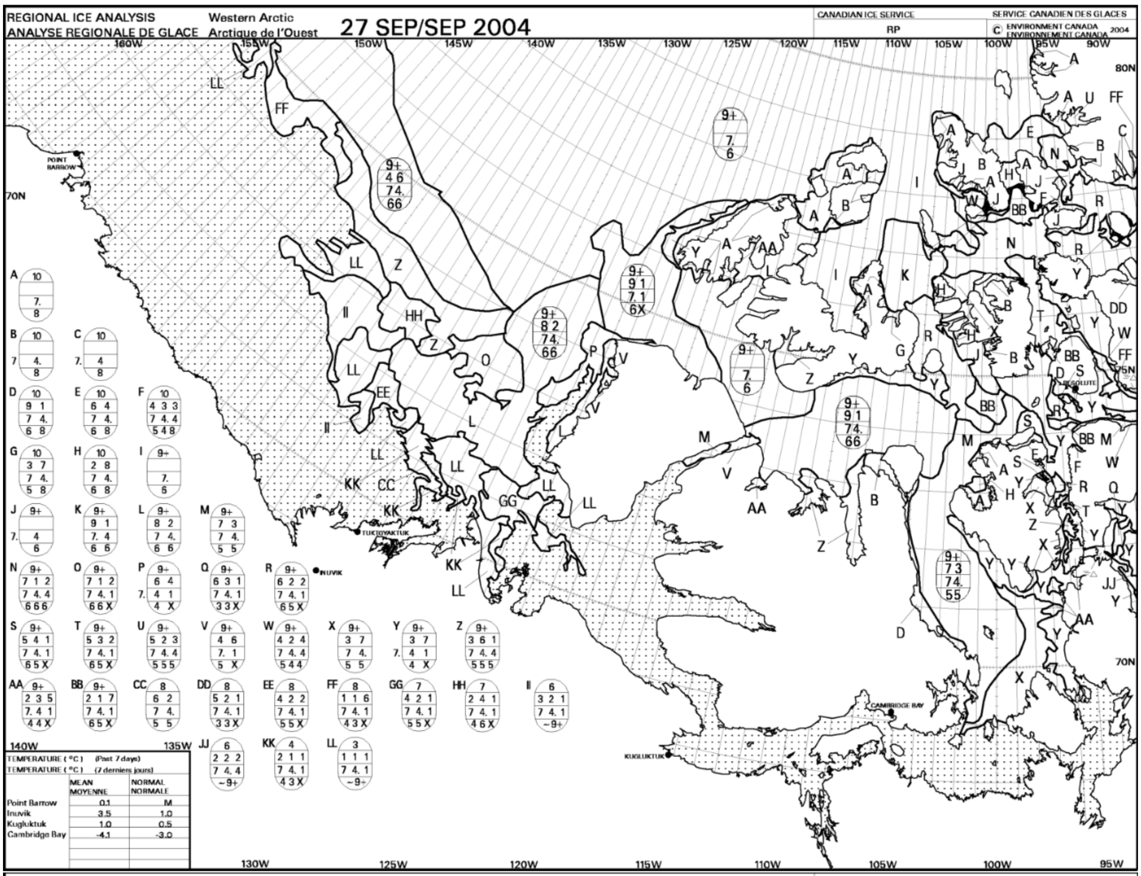
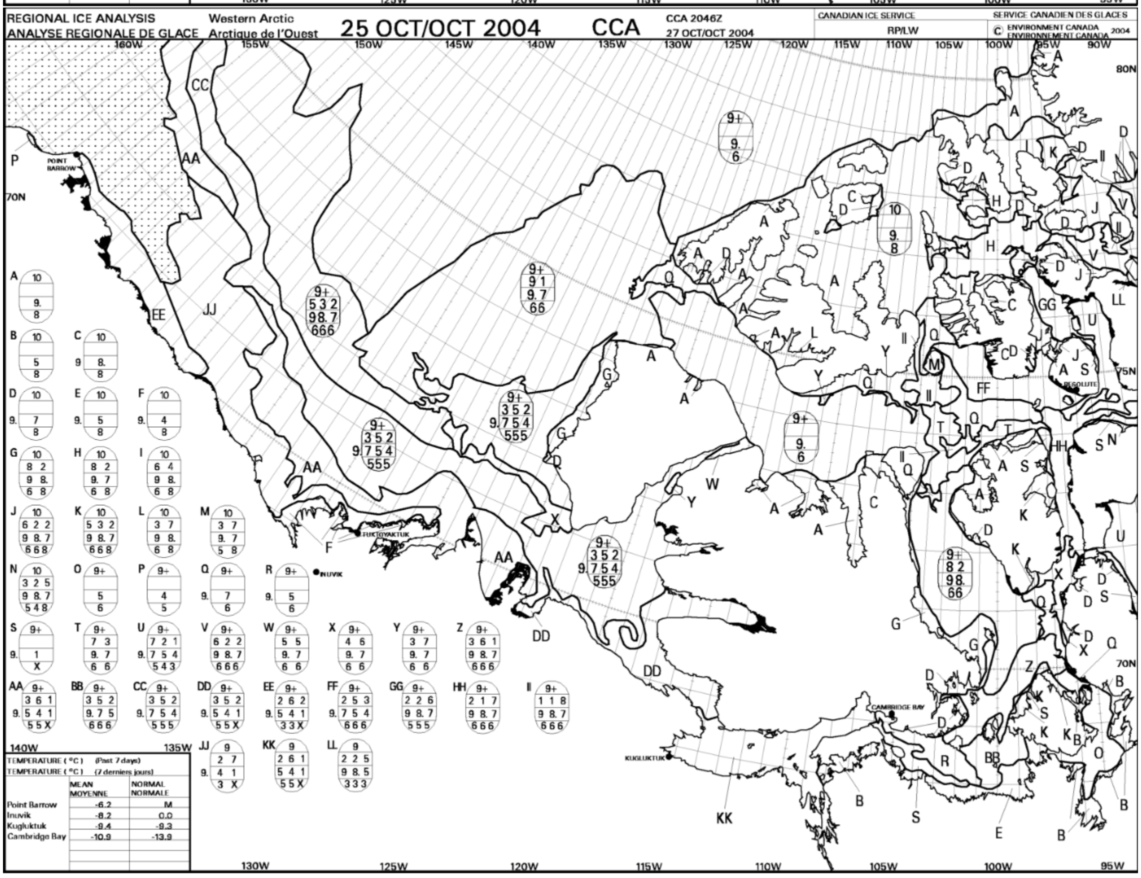
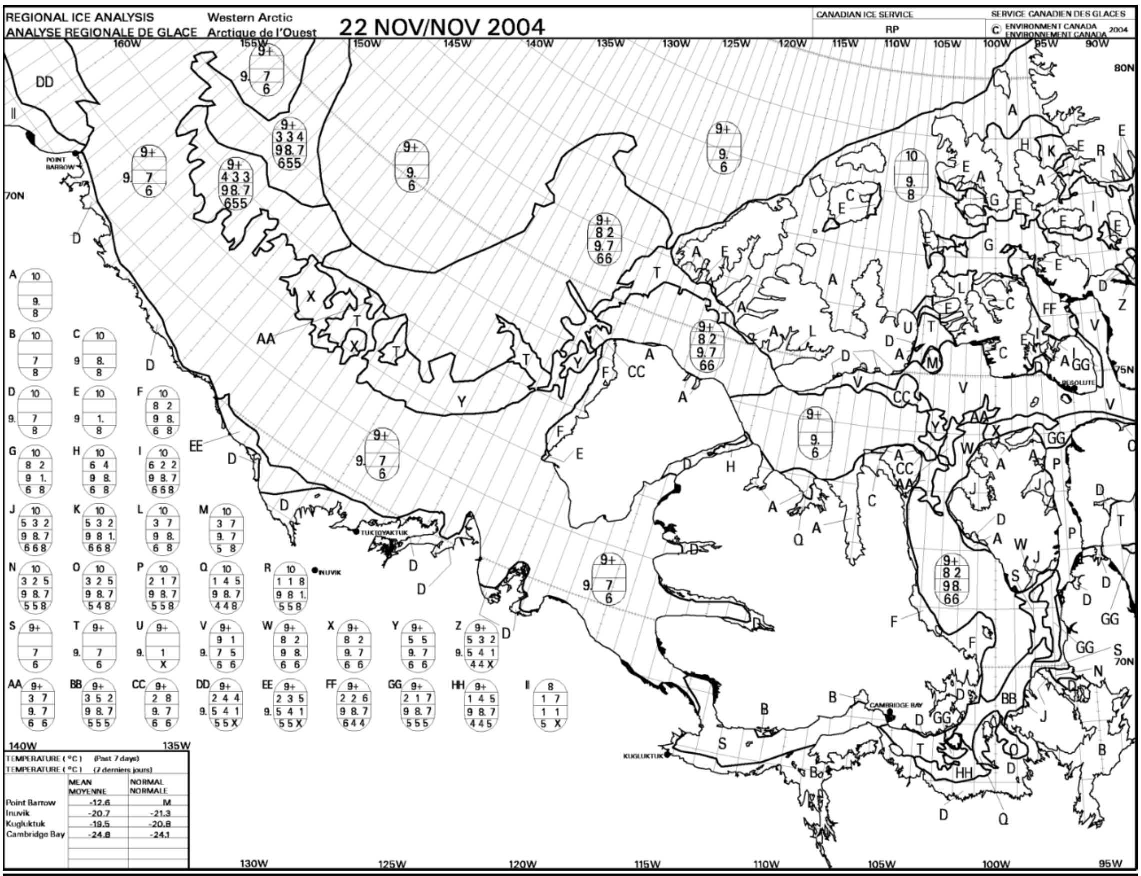
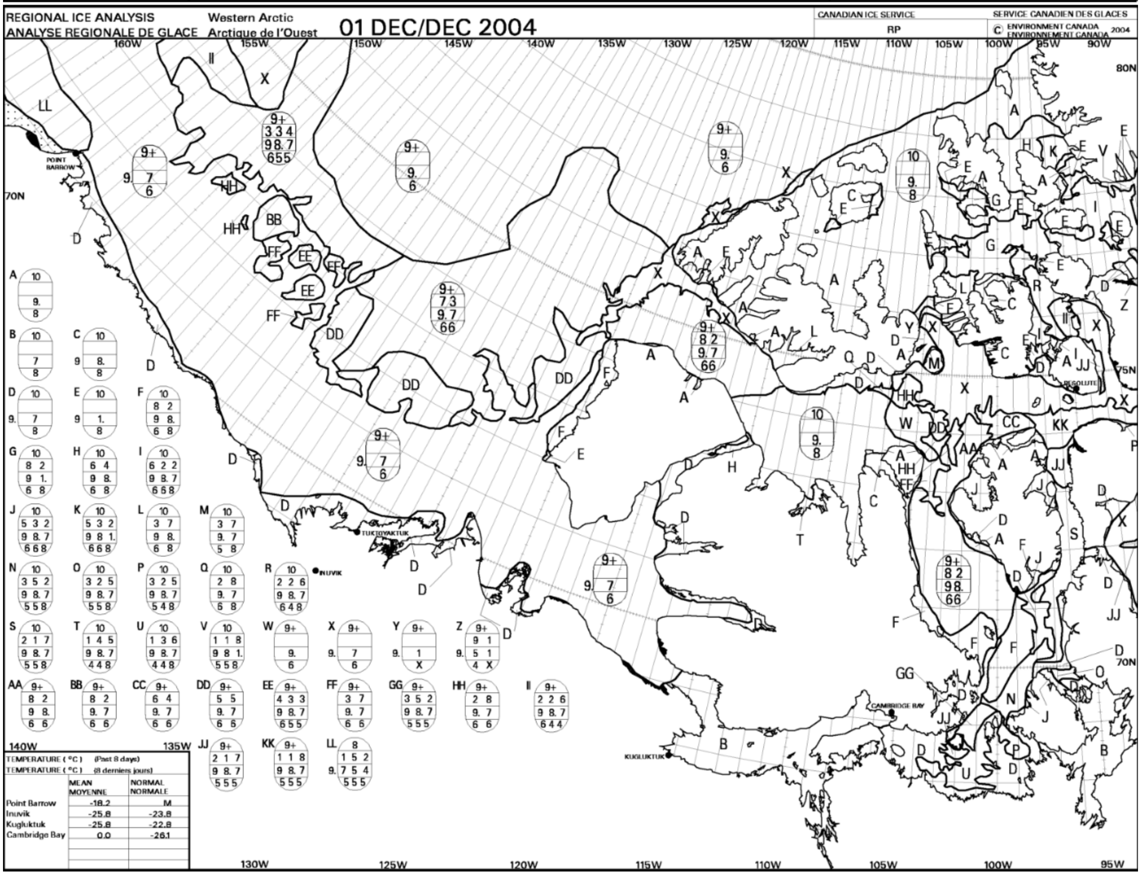
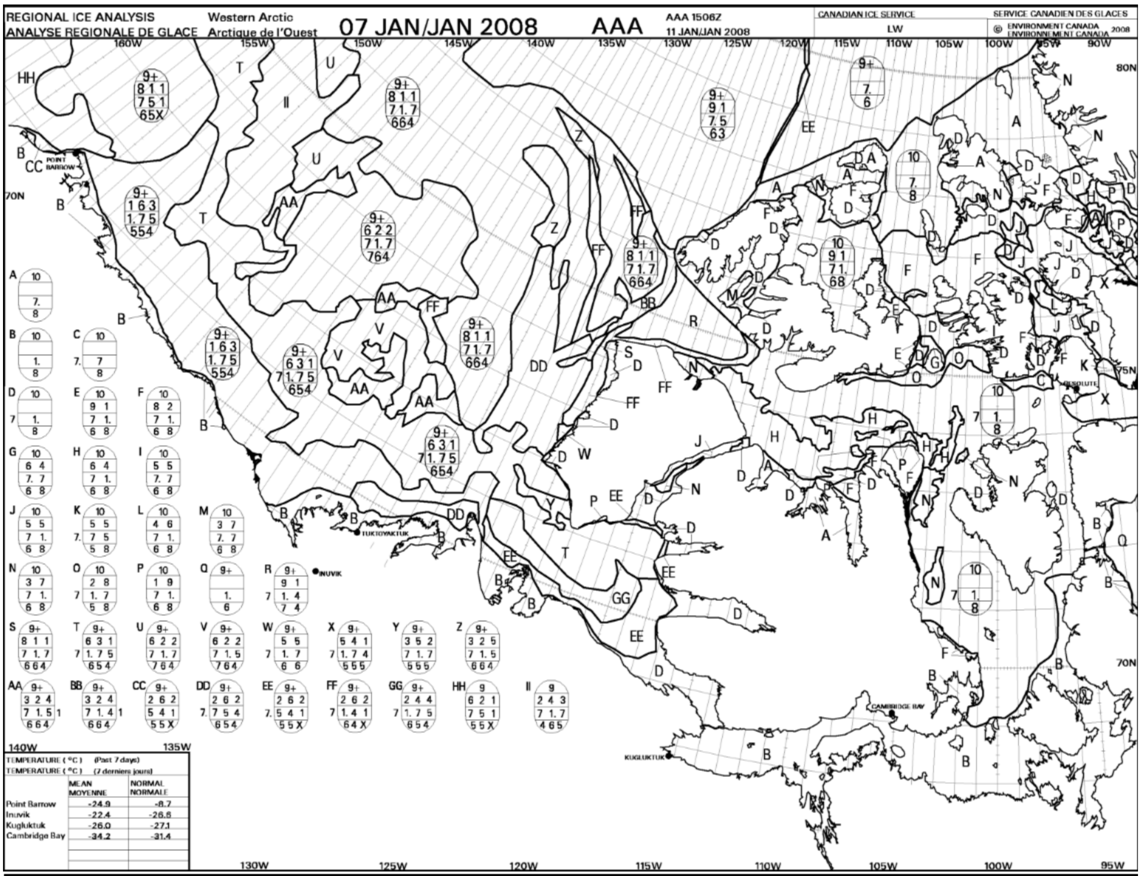
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow 4.1 2.0
Inuvik 5.3 6.4
Kugluktuk 5.5 6.7
Cambridge Bay 4.3 4.2

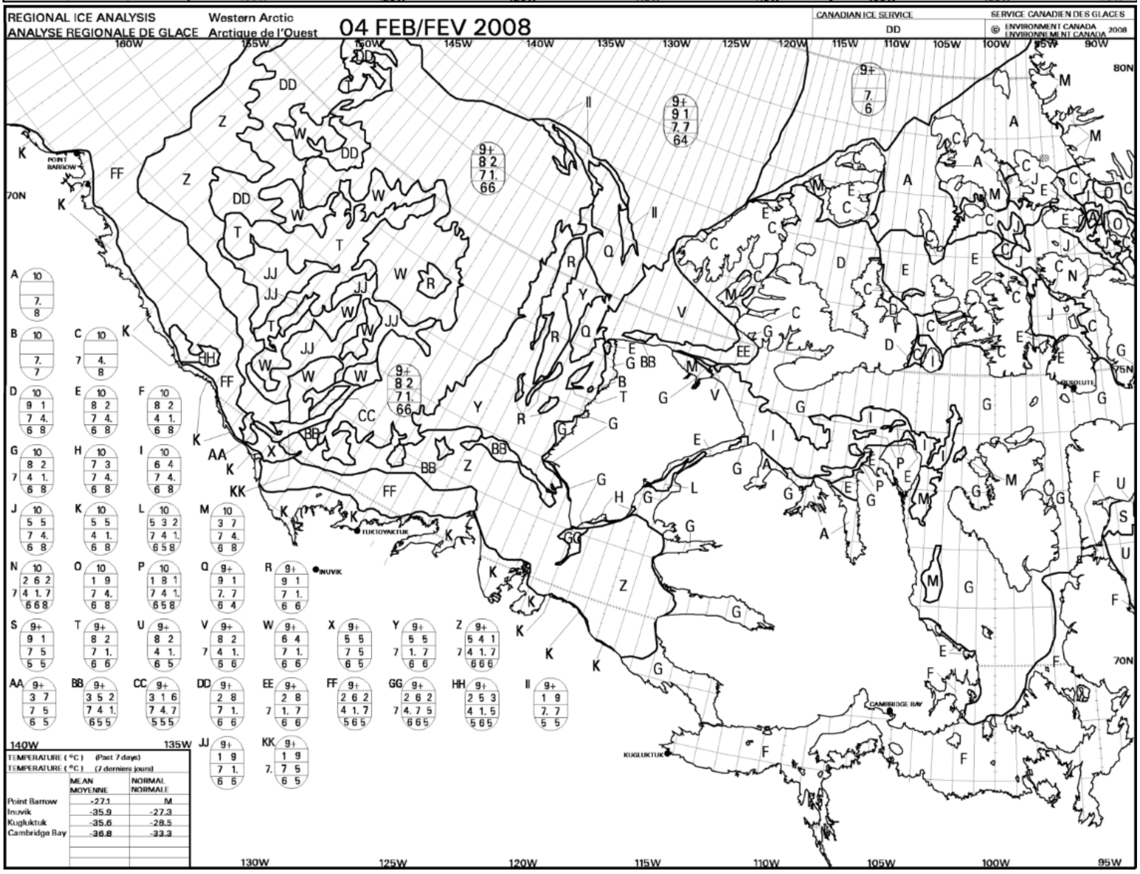

REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
27 SEP/SEP 2004
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
RP
ENVIRONMENT CANADA
ENVIRONNEMENT CANADA
2004
POINT BARROW
TUKTOYAKTUK
INUVIK
CAMBRIDGE BAY
KUGLUKTUK
RESOLUTE
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow 0.1 M
Inuvik 3.5 1.0
Kugluktuk 1.0 0.5
Cambridge Bay -4.1 -3.0


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
25 OCT/OCT 2004
CCA
CCA 2046Z
27 OCT/OCT 2004
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
RP/LW
ENVIRONMENT CANADA
ENVIRONNEMENT CANADA
2004
POINT BARROW
TUKTOYAKTUK
INUVIK
CAMBRIDGE BAY
KUGLUKTUK
RESOLUTE
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow -6.2 M
Inuvik -8.2 0.0
Kugluktuk -9.4 -9.3
Cambridge Bay -10.9 -13.9


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
22 NOV/NOV 2004
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
ENVIRONMENT CANADA
ENVIRONNEMENT CANADA
POINT BARROW
TUKTOYAKTUK
INUVIK
CAMBRIDGE BAY
KUGLUKTUK
RESOLUTE
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow -12.6 M
Inuvik -20.7 -21.3
Kugluktuk -19.5 -20.8
Cambridge Bay -24.8 -24.1


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
01 DEC/DEC 2004
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
ENVIRONMENT CANADA
ENVIRONNEMENT CANADA
POINT BARROW
TUKTOYAKTUK
INUVIK
CAMBRIDGE BAY
KUGLUKTUK
RESOLUTE
TEMPERATURE (°C) (Past 8 days)
TEMPERATURE (°C) (8 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow -18.2 M
Inuvik -25.8 -23.8
Kugluktuk -25.8 -22.8
Cambridge Bay 0.0 -26.1


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
07 JAN/JAN 2008
AAA
AAA 1506Z
11 JAN/JAN 2008
CANADIAN ICE SERVICE
LW
SERVICE CANADIEN DES GLACES
© ENVIRONMENT CANADA
ENVIRONNEMENT CANADA 2008
POINT BARROW
TUKTOYAKTUK
INUVIK
RESOLUTE
CAMBRIDGE BAY
KUGLUKTUK
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE | NORMAL NORMALE
Point Barrow -24.9 -8.7
Inuvik -22.4 -26.8
Kugluktuk -26.0 -27.1
Cambridge Bay -34.2 -31.4


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
04 FEB/FEV 2008
CANADIAN ICE SERVICE
DD
SERVICE CANADIEN DES GLACES
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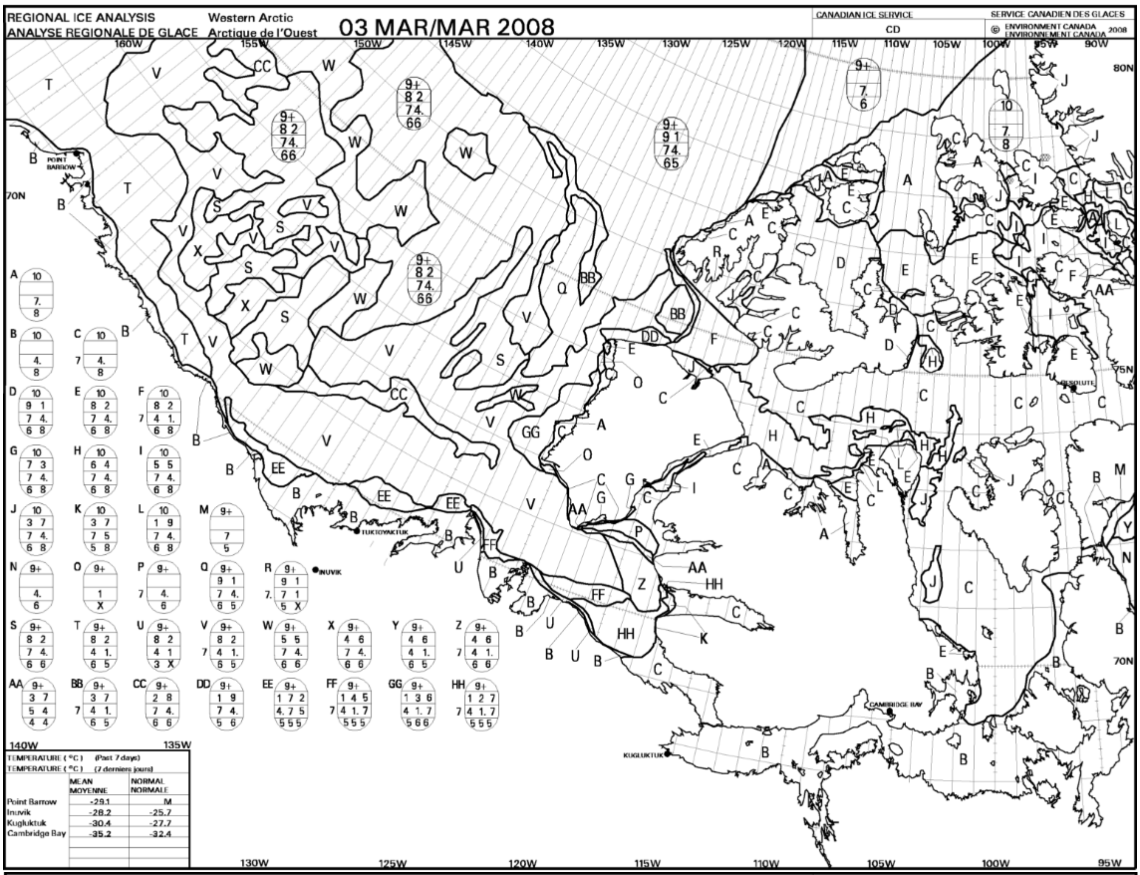
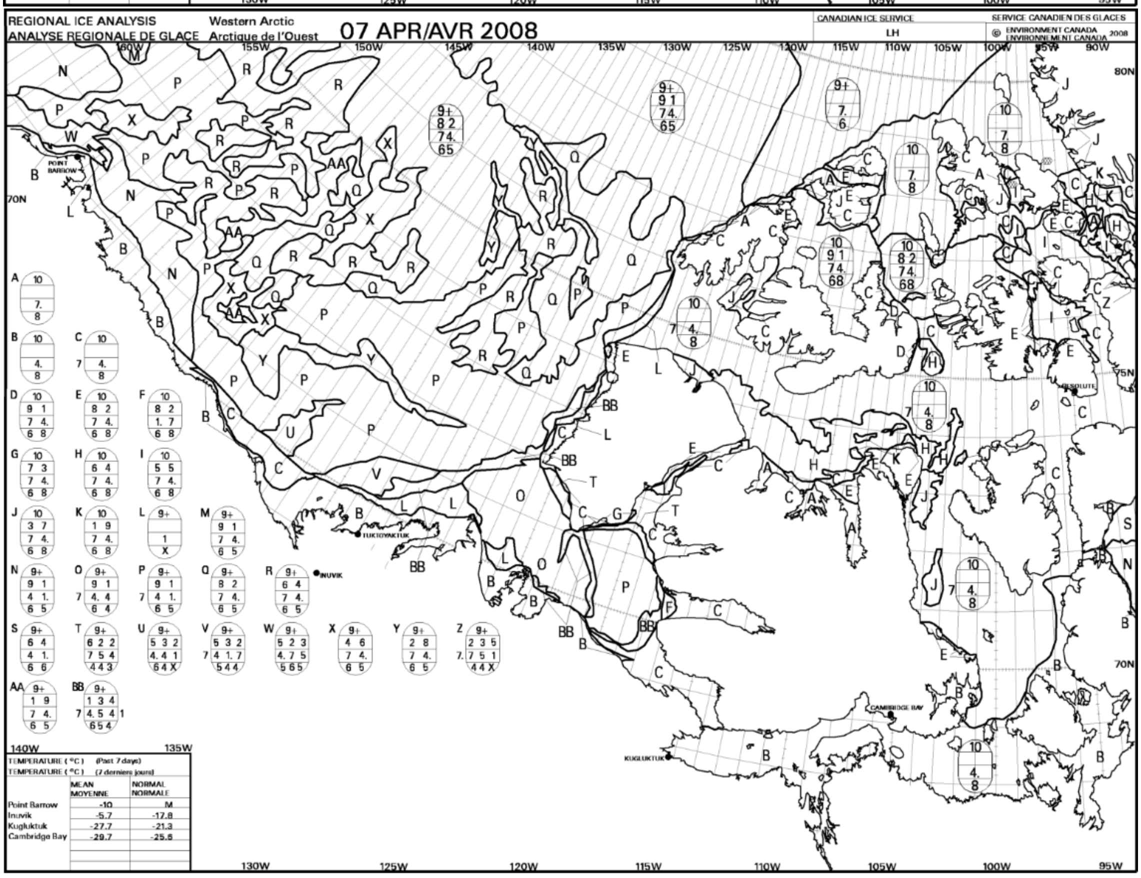
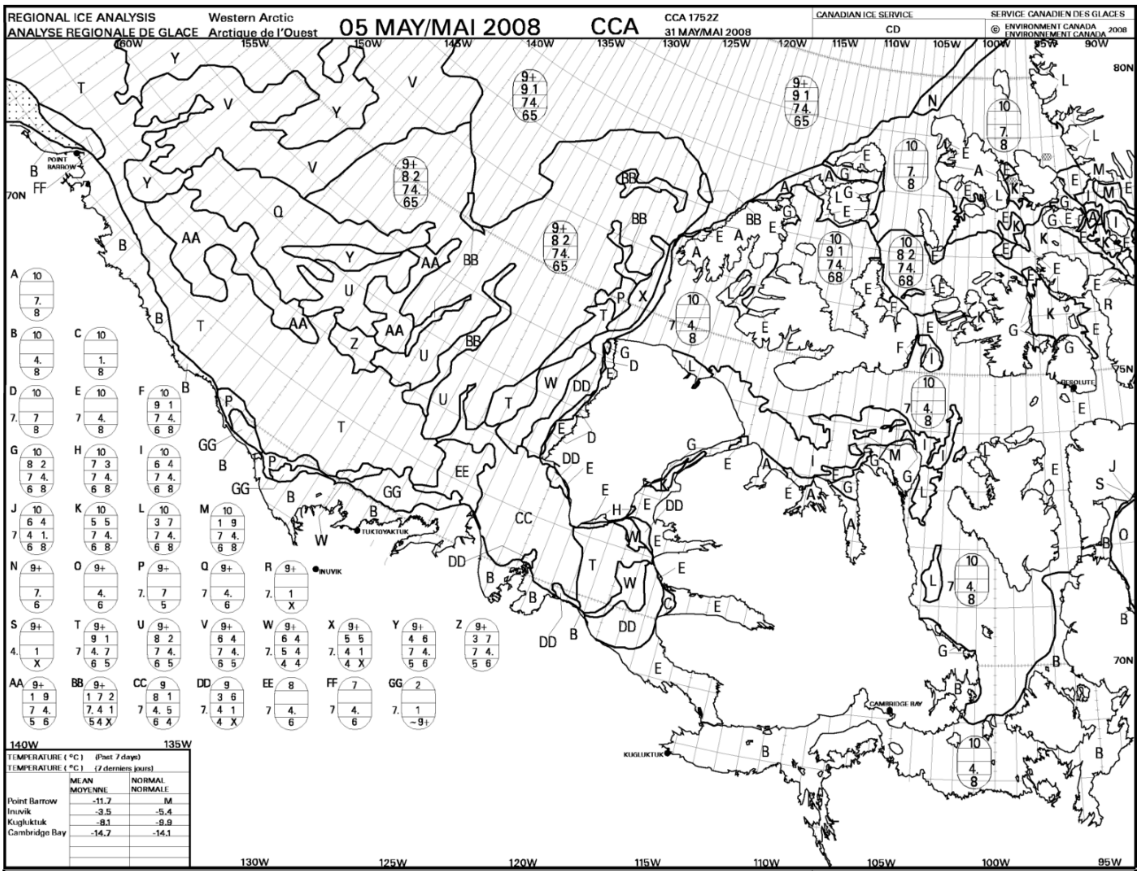
ENVIRONNEMENT CANADA 2008
POINT BARROW
TUKTOYAKTUK
INUVIK
RESOLUTE
CAMBRIDGE BAY
KUGLUKTUK
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE | NORMAL NORMALE
Point Barrow -27.1 M
Inuvik -35.9 -27.3
Kugluktuk -35.6 -28.5
Cambridge Bay -36.8 -33.3


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
03 MAR/MAR 2008
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
ENVIRONMENT CANADA
POINT BARROW
TUKTOYAKTUK
INUVIK
RESOLUTE
CAMBRIDGE BAY
KUGLUKTUK
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow -29.1 M
Inuvik -28.2 -25.7
Kugluktuk -30.4 -27.7
Cambridge Bay -35.2 -32.4


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
07 APR/AVR 2008
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
ENVIRONMENT CANADA
POINT BARROW
TUKTOYAKTUK
INUVIK
RESOLUTE
CAMBRIDGE BAY
KUGLUKTUK
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow -10 M
Inuvik -5.7 -17.8
Kugluktuk -27.7 -21.3
Cambridge Bay -29.7 -25.6


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
05 MAY/MAI 2008
CCA
CCA 1752Z
31 MAY/MAI 2008
CANADIAN ICE SERVICE
CD
SERVICE CANADIEN DES GLACES
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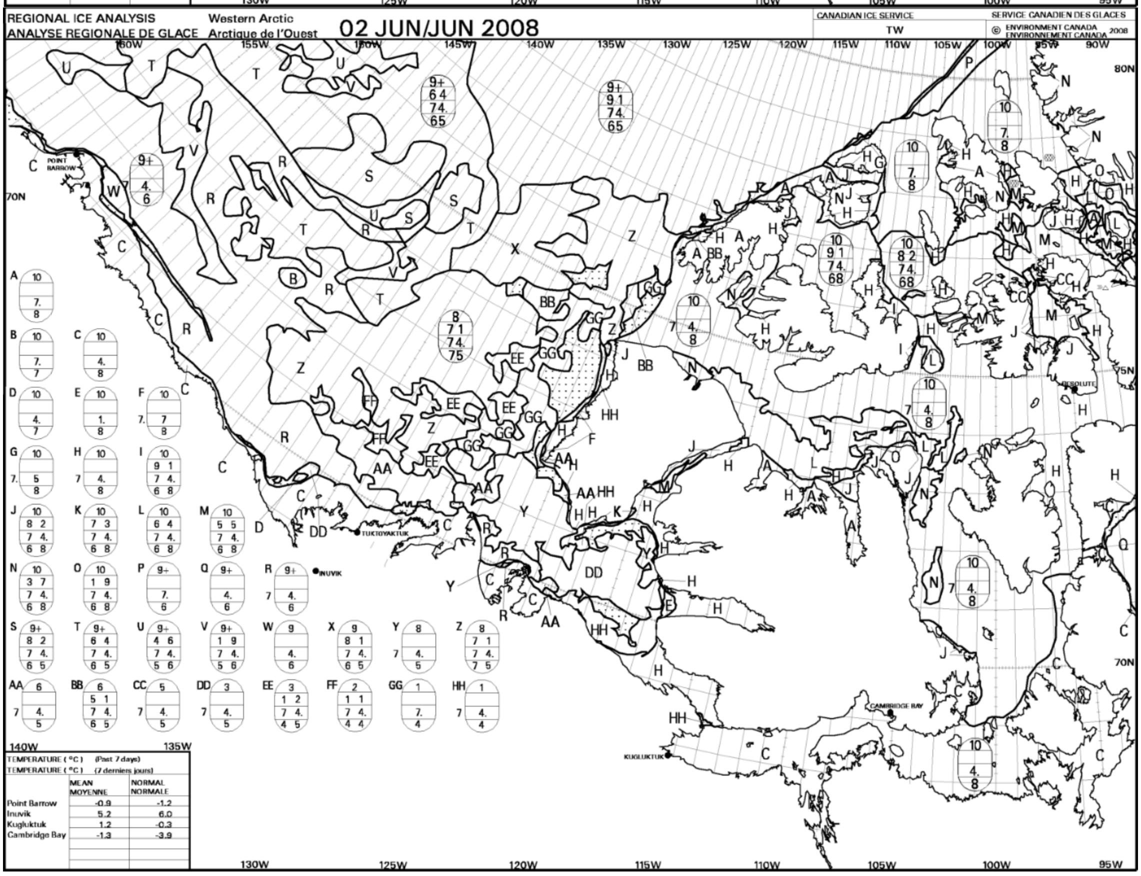
POINT BARROW
TUKTOYAKTUK
INUVIK
RESOLUTE
CAMBRIDGE BAY
KUGLUKTUK
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow -11.7 M
Inuvik -3.5 -5.4
Kugluktuk -8.1 -9.9
Cambridge Bay -14.7 -14.1


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
02 JUN/JUN 2008
CANADIAN ICE SERVICE
TW
SERVICE CANADIEN DES GLACES
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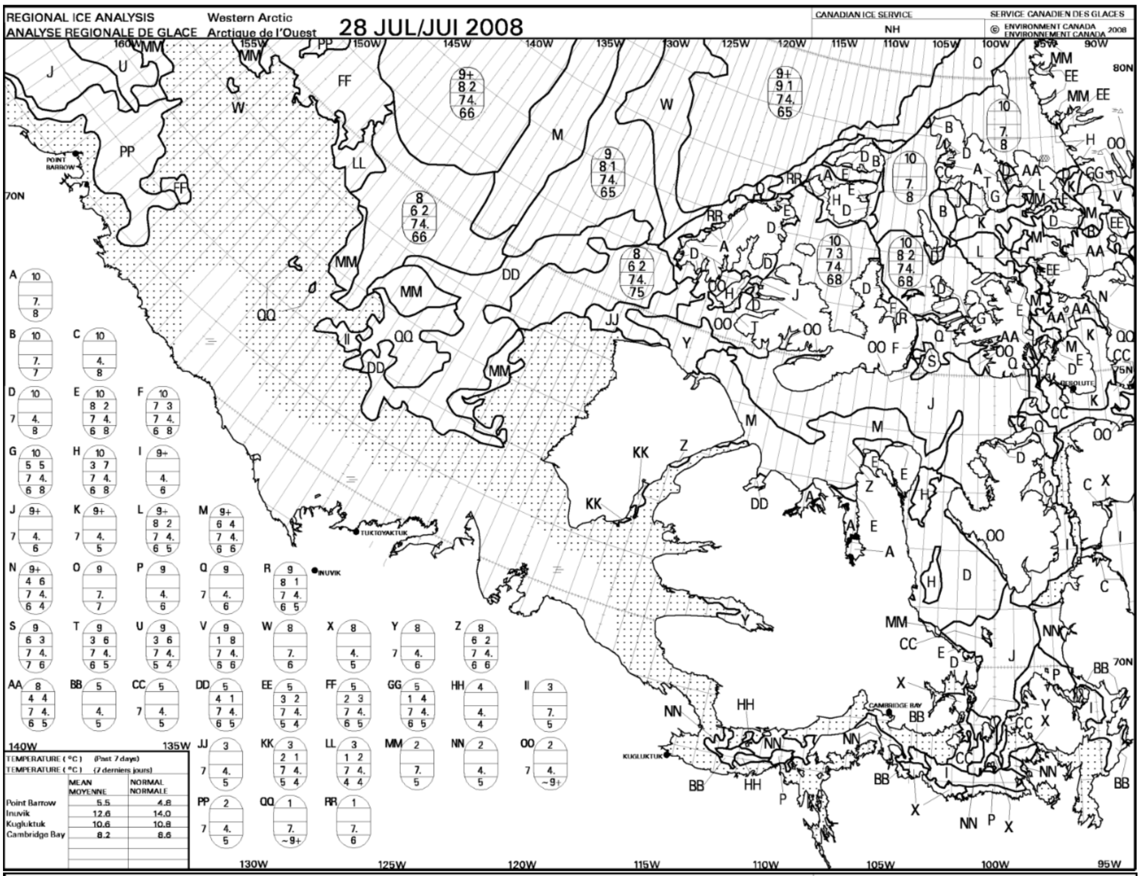
POINT BARROW
TUKTOYAKTUK
INUVIK
RESOLUTE
CAMBRIDGE BAY
KUGLUKTUK
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow -0.9 -1.2
Inuvik 5.2 6.0
Kugluktuk 1.2 -0.3
Cambridge Bay -1.3 -3.9


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
28 JUL/JUI 2008
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
NH
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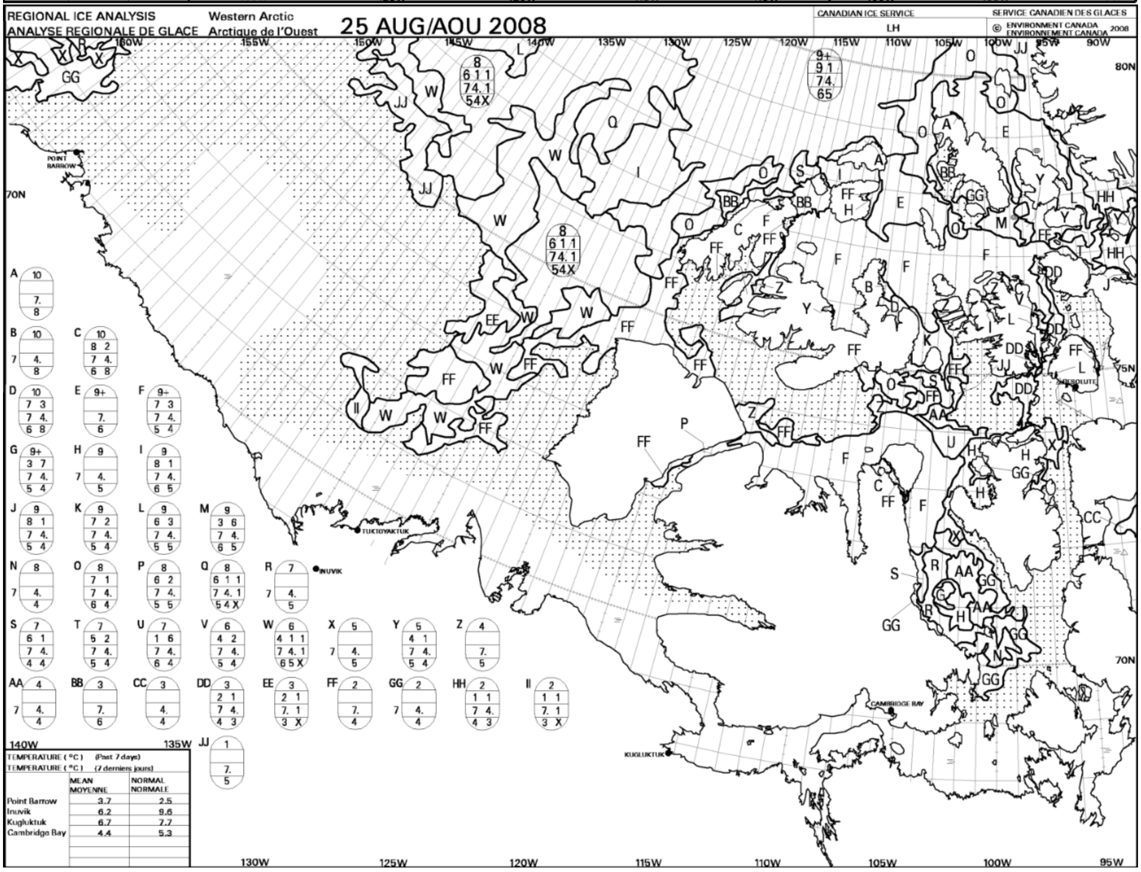
POINT BARROW
TUKTOYAKTUK
INUVIK
KUGLUKTUK
CAMBRIDGE BAY
RESOLUTE
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow 5.5 4.6
Inuvik 12.6 14.0
Kugluktuk 10.6 10.8
Cambridge Bay 8.2 6.6


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
25 AUG/AOU 2008
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
LH
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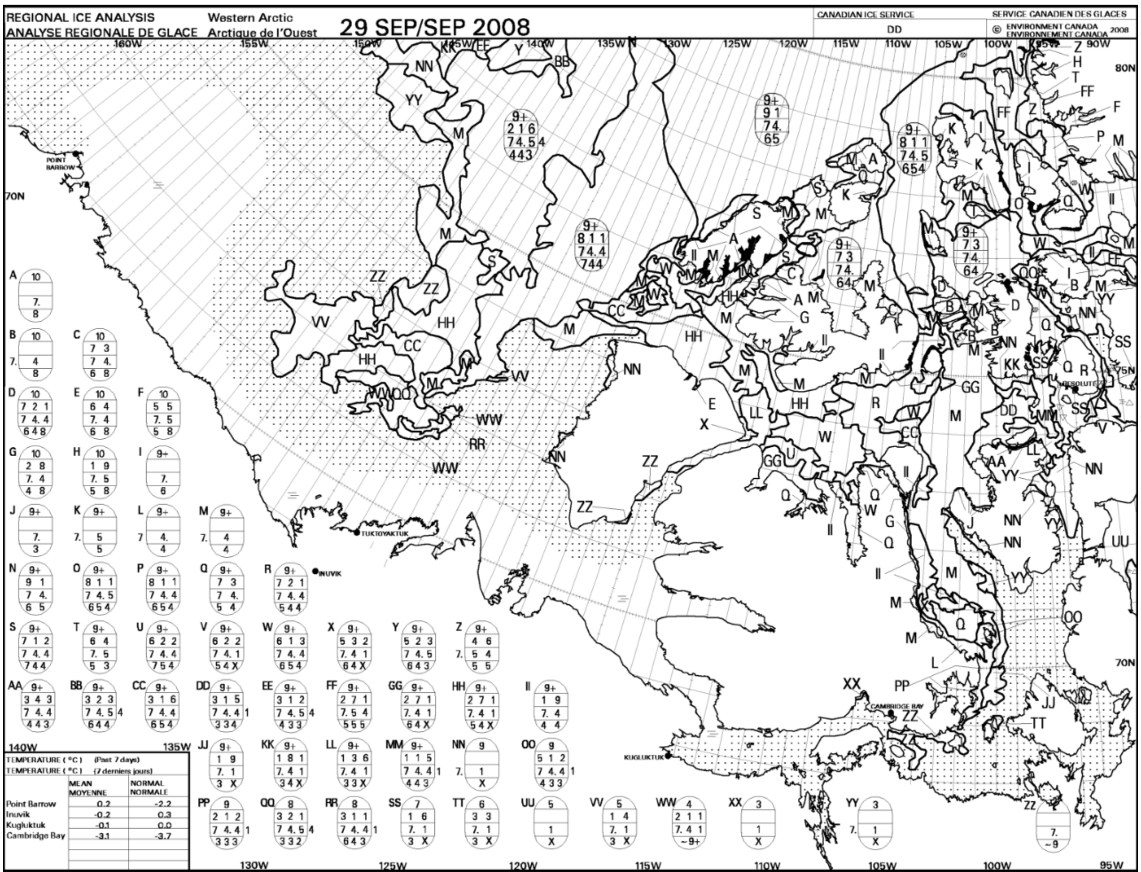
POINT BARROW
TUKTOYAKTUK
INUVIK
KUGLUKTUK
CAMBRIDGE BAY
RESOLUTE
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow 3.7 2.5
Inuvik 6.2 9.6
Kugluktuk 6.7 7.7
Cambridge Bay 4.4 5.3


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
29 SEP/SEP 2008
CANADIAN ICE SERVICE
DD
SERVICE CANADIEN DES GLACES
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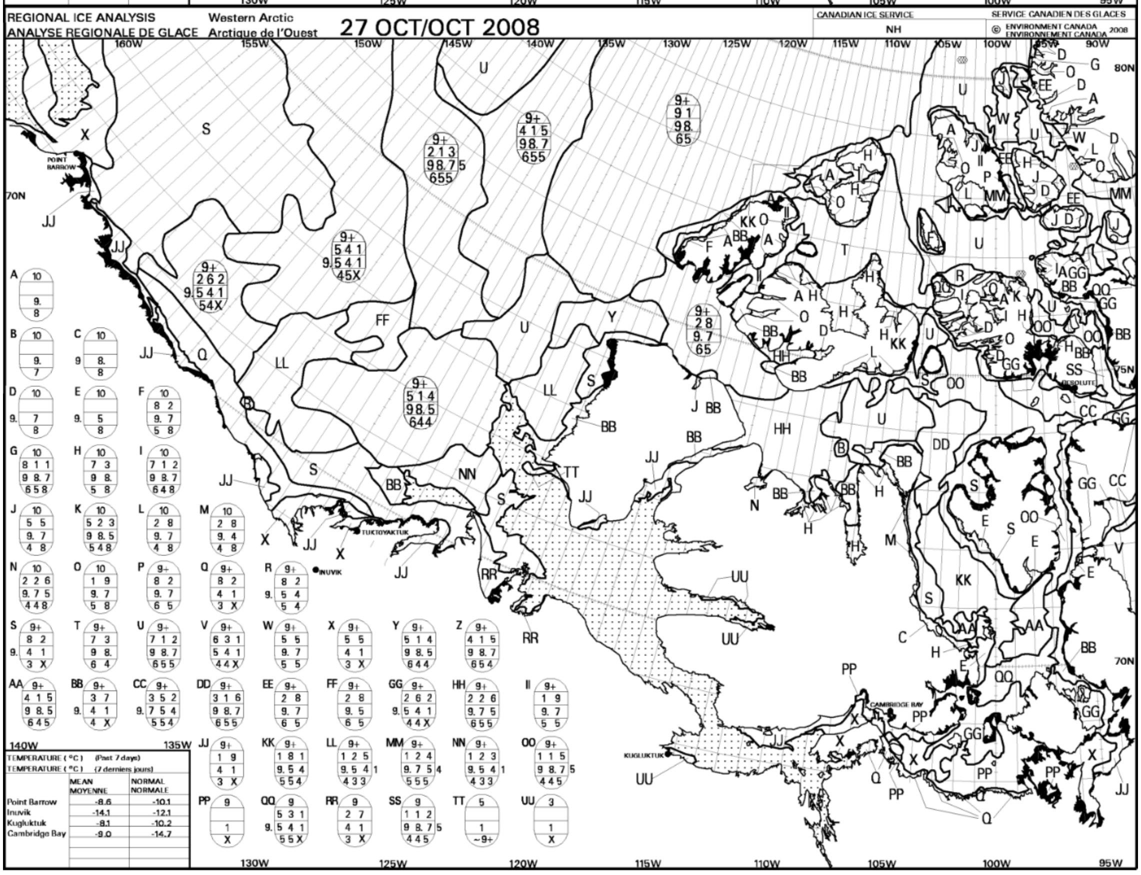
POINT BARROW
TUKTOYAKTUK
INUVIK
KUGLUKTUK
CAMBRIDGE BAY
RESOLUTE
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow 0.2 -2.2
Inuvik -0.2 0.3
Kugluktuk -0.1 0.0
Cambridge Bay -3.1 -3.7


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
27 OCT/OCT 2008
CANADIAN ICE SERVICE
NH
SERVICE CANADIEN DES GLACES
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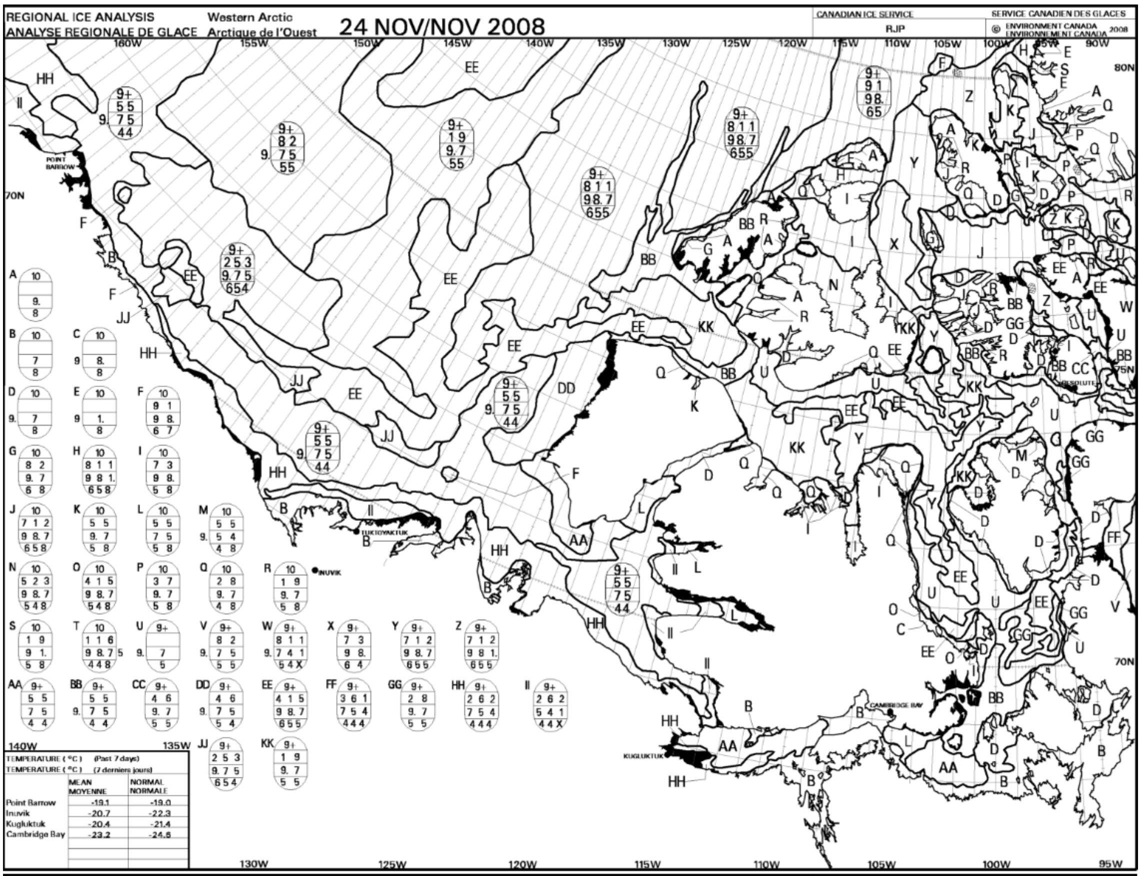
POINT BARROW
TUKTOYAKTUK
INUVIK
KUGLUKTUK
CAMBRIDGE BAY
RESOLUTE
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow -8.6 -10.1
Inuvik -14.1 -12.1
Kugluktuk -8.1 -10.2
Cambridge Bay -9.0 -14.7


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
24 NOV/NOV 2008
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
RJP
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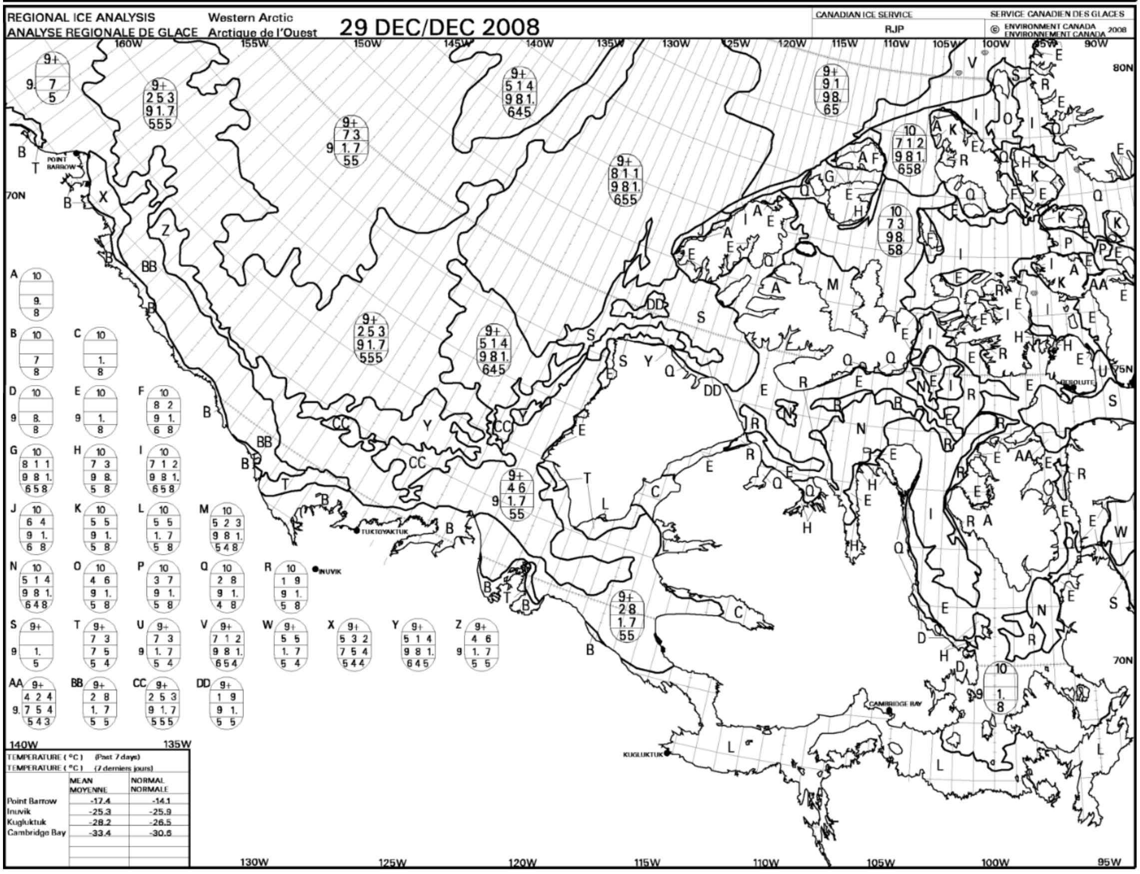
ENVIRONNEMENT CANADA 2008
POINT BARROW
TUKTOYAKTUK
INUVIK
KUGLUKTUK
CAMBRIDGE BAY
RESOLUTE
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow -19.1 -19.0
Inuvik -20.7 -22.3
Kugluktuk -20.4 -21.4
Cambridge Bay -23.2 -24.6


REGIONAL ICE ANALYSIS
ANALYSE REGIONALE DE GLACE
Western Arctic
Arctique de l'Ouest
29 DEC/DEC 2008
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
RJP
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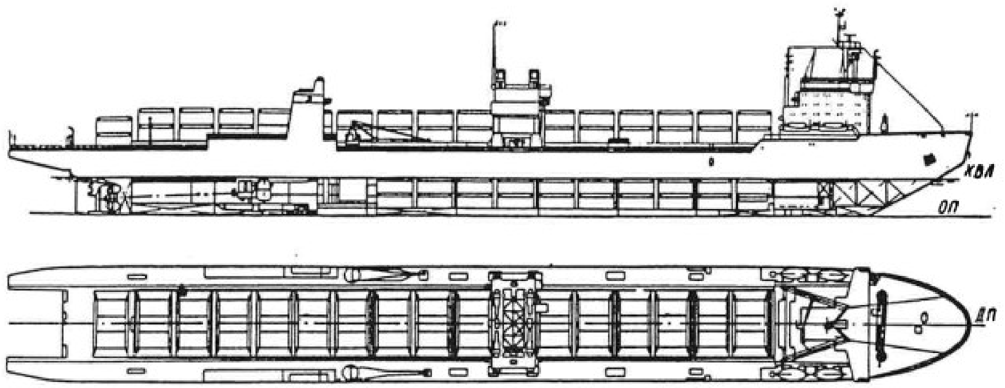
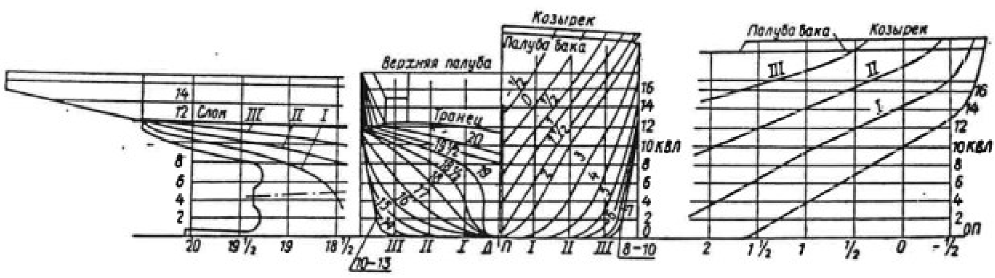
ENVIRONNEMENT CANADA 2008
POINT BARROW
TUKTOYAKTUK
INUVIK
KUGLUKTUK
CAMBRIDGE BAY
RESOLUTE
TEMPERATURE (°C) (Past 7 days)
TEMPERATURE (°C) (7 derniers jours)
MEAN MOYENNE
NORMAL NORMALE
Point Barrow -17.4 -14.1
Inuvik -25.3 -25.9
Kugluktuk -28.2 -26.5
Cambridge Bay -33.4 -30.6

C - 25

SEVMORPUT





L_{WL}	= 260.3 m
B_{WL}	= 32.2 m
T_{WL}	= 10.7 m
Δ	= 61 000 t
Shaft power	= 29 420 kW

Data from Simov et al. (1981).

NAUTICUS hull by DNV Software	**IACS Unified req. for polar class ships** **Ships for Navigation in Ice, July 2013**	
2016-06-06 Ver. 17.90.85.9682	<Master's Thesis VE & Arctic Cruise Ship>	<VE>

Main Data

Notation: PC5

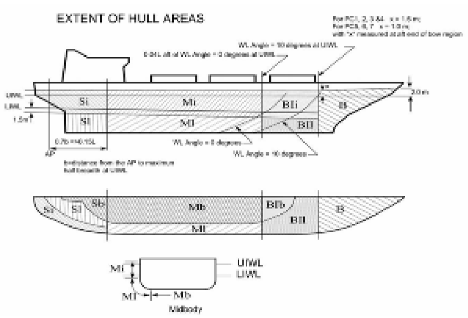
Ship id:

Add. Notation Icebreaker: ☐

Designed for astern operation: ☑

Rule length: 265,63 [m]

Displacement: 50 [kT]



Design Load Patch

	B	BI_i	BI_l	BI_b	MI_i	MI_l	MI_b	SI_i	SI_l	SI_b	S_i	S_l	S_b
w [m]	3,06	3,31	3,31	3,31	3,31	3,31	3,31	3,31	3,31	3,31	Error	Error	Error
b [m]	0,62	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	0,92	Error	Error	Error
P_{avg}	4,48	4,48	4,48	4,48	4,48	4,48	4,48	4,48	4,48	4,48	Error	Error	Error

Only used for vessels designed for astern operation

Subregions

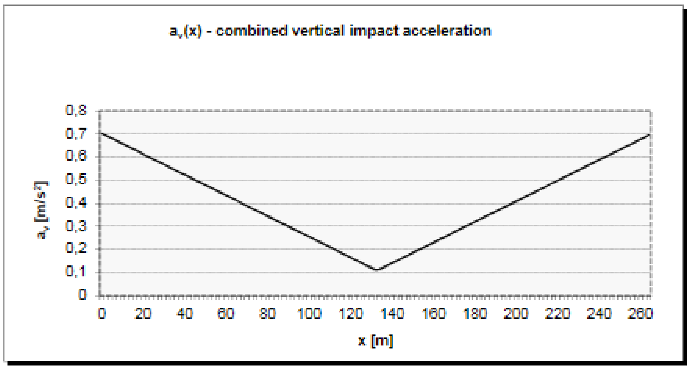
Bow Area subregions

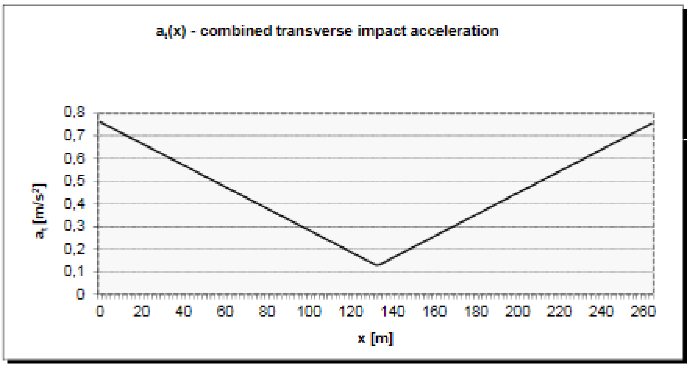
	i	1	2	3	4
[m]	x	11,30	33,80	55,80	77,70
[°]	α	16,0	15,0	12,0	3,0
[°]	β'	40,9	44,0	39,4	24,0
[-]	fa_i	0,22	0,22	0,18	0,05
[-]	*Failure*	Crushing	Crushing	Crushing	Crushing
[MN]	F_i	8,45	8,28	6,85	1,93
[MN/m]	Q_i	2,77	2,68	2,46	1,33
[MPa]	P_i	4,42	4,48	4,18	2,77

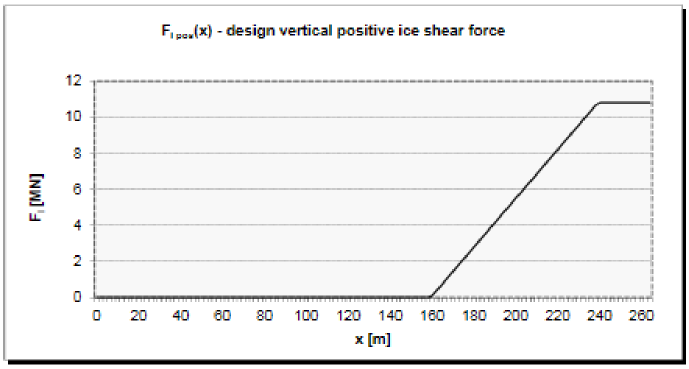
Stern Area Subregions

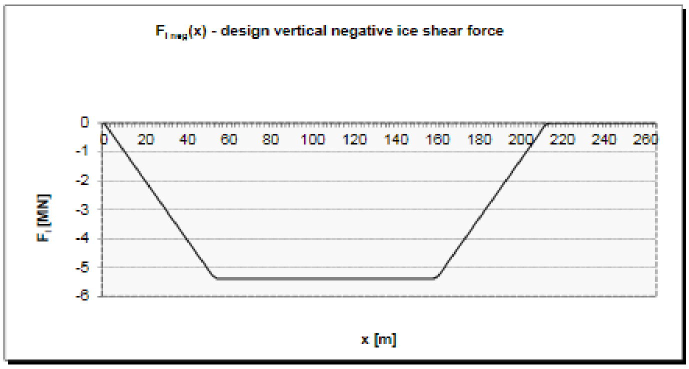
	i
[m]	x
[°]	α
[°]	β'
[-]	fa_i
[-]	*Failure*
[MN]	F_i
[MN/m]	Q_i
[MPa]	P_i

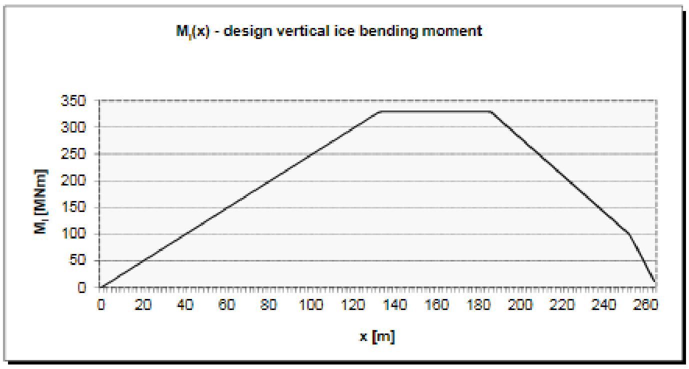
x [m]	260,00
B [m]	35,80
H [m]	0,00
A_{wp} [m²]	8500,00
α_{stem} [°]	25,0
γ_{stem} [°]	30,0
Φ [°]	90,0
e_b	0
WL Angle = 0 at UIWL [m]	0,00
F_{IB} [MN]	10,8
F_{Ipos} [MN]	10,8
F_{Ineg} [MN]	0
M_I [MNm]	41,907273
a_v [m/s²]	0,6768205
a_t [m/s²]	0,7339971
a_l [m/s²]	-0,411535





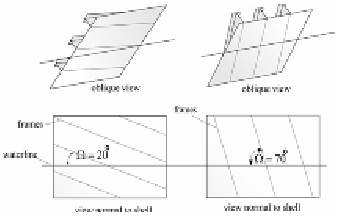

$F_{I\,pos}(x)$ - design vertical positive ice shear force
F_I [MN]
12
10
8
6
4
2
0
0 20 40 60 80 100 120 140 160 180 200 220 240 260
x [m]

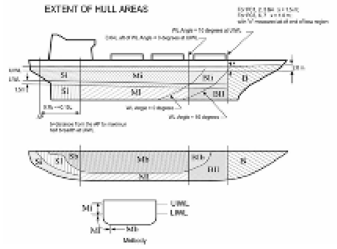

$F_{I\,neg}(x)$ - design vertical negative ice shear force
F_I [MN]
0
-1
-2
-3
-4
-5
-6
0 20 40 60 80 100 120 140 160 180 200 220 240 260
x [m]


$M_I(x)$ - design vertical ice bending moment
M_I [MNm]
350
300
250
200
150
100
50
0
0 20 40 60 80 100 120 140 160 180 200 220 240 260
x [m]

Nauticus Hull
2016-06-06
Ver. 17.90.85.9682

IACS Unified req. for polar class ships <Master's Thesis VE Arctic Cruise Ship>
Ships for Navigation in Ice, July 2013
Shell plating





Id	Hull Area	s	l	t_s	σ_F	Framing	Ω	PPF_p	AF	b	t_{net}	t_{req}	t_p	
	[-]	[m]	[m]	[mm]	[N/mm²]	[-]	[°]	[-]	[-]	[m]	[mm]	[mm]	[mm]	
p1	Midbody Icebelt	0,34	2,56	2,00	490,00	Long	0,0	1,80	0,50	0,92	14,50	16,50	29,00	Pass
p2	Midbody Lower	0,34	2,56	2,00	490,00	Long	0,0	1,80	0,30	0,92	11,00	13,00	23,00	Pass
p3	Midbody Lower	0,43	2,56	2,00	355,00	Trans	90,0	1,37	0,30	0,92	12,50	14,50	16,00	Pass
p4	Midbody Bottom	0,34	2,56	2,00	490,00	Long	0,0						16,00	NA
p5	Bow Intermediate Icebelt	0,34	2,56	2,00	490,00	Long	0,0	1,80	0,80	0,92	18,00	20,00	16,00	Fail
p6	Bow Intermediate Lower	0,34	2,56	2,00	490,00	Long	0,0	1,80	0,55	0,92	15,00	17,00	16,00	Fail
p7	Bow Intermediate Bottom	0,34	2,56	2,00	490,00	Long	0,0	1,80	0,35	0,92	12,00	14,00	16,00	Pass
p8	Stern Intermediate Icebelt	0,34	2,56	2,00	490,00	Long	0,0	1,80	0,80	0,92	18,00	20,00	16,00	Fail
p9	Stern Intermediate Lower	0,34	2,56	2,00	490,00	Long	0,0	1,80	0,55	0,92	15,00	17,00	16,00	Fail
p10	Stern Intermediate Bottom	0,34	2,56	2,00	490,00	Long	0,0	1,80	0,35	0,92	12,00	14,00	16,00	Pass
p11	Bow	0,43	2,56	2,00	490,00	Trans	90,0	1,37	1,00	0,62	18,00	20,00	16,00	Fail
p12	Midbody Icebelt	0,43	2,56	2,00	490,00	Trans	90,0	1,37	0,50	0,92	13,50	15,50	16,00	Pass

IACS Unified req. for polar class ships
Ships for Navigation in Ice, July 2013
Local frames

		Id	lf1	lf2	lf3	lf4	lf5	lf6	lf7	lf8	lf9	lf10	lf13
		Hull area	Midbody Icebelt	Midbody Lower	Midbody Lower	Bow Intermediate Icebelt	Bow Intermediate Lower	Bow Intermediate Bottom	Bow	Stern Intermediate Icebelt	Stern Intermediate Lower	Stern Intermediate Bottom	Midbody Icebelt
		s [m]	0,34	0,34	0,43	0,34	0,34	0,34	0,43	0,34	0,34	0,34	0,43
		σ_F [N/mm2]	390,00	390,00	390,00	390,00	390,00	390,00	390,00	390,00	390,00	390,00	390,00
		Framing	Long	Long	Trans	Long	Long	Long	Trans	Long	Long	Long	Trans
		Ω [°]	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	90,0
		t_c [mm]	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
		t_{pn} [mm]	14,50	11,00	12,50	18,00	15,00	12,00	18,00	18,00	15,00	12,00	15,50
		a [m]	2,56	2,56	1,65	2,56	2,56	2,56	2,20	2,56	2,56	2,56	1,00
		φ_w [°]	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0	90,0
		S_w [m]	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6
		h [mm]	320,00	240,00	200,00	430,00	340,00	260,00	430,00	430,00	340,00	430,00	240,00
		b_f [mm]	58,76	45,82	39,35	79,18	62,75	48,81	79,18	79,18	62,75	79,18	43,82
		$b_{f\ out}$ [mm]	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
		t_f [mm]	32,78	24,09	19,74	44,74	34,96	26,26	44,74	44,74	34,96	44,74	24,09
		h_{fc} [mm]	303,61	227,96	190,13	407,63	322,52	246,87	407,63	407,63	322,52	407,63	227,96
		b_w [mm]	9,89	6,04	4,12	13,87	10,48	7,13	13,87	13,87	10,48	13,87	7,04
		t_w [mm]	13,00	12,00	11,50	17,00	14,00	12,00	17,00	17,00	14,00	17,00	11,00
		h_w [mm]	287,22	215,91	180,26	385,26	305,04	233,74	385,26	385,26	305,04	385,26	215,91
		Flange	Tee	Tee	Tee	Tee	Tee	Tee	Tee	Tee	Tee	Tee	Tee
		End Fixity	Both ends fixed	Both ends fixed	Both ends fixed	Both ends fixed	Both ends fixed	Both ends fixed	Both ends fixed	Both ends fixed	Both ends fixed	Both ends fixed	Both ends fixed
		With end bracket	No	No	Yes	No	No	No	Yes	No	No	Yes	Yes
		Load distrib stringers	No	No	No	No	No	No	Yes	No	No	No	Yes
		$A_{w\ input}$ [cm²]											
		A_w [cm²]	38,40	26,40	21,00	68,80	44,20	28,60	68,80	68,80	44,20	68,80	24,00
		Z_p [cm³]	1093,73	516,45	327,24	2456,64	1309,52	627,69	2609,44	2456,64	1309,52	2137,39	488,31
		P_{avg} [MPa]	4,48	4,48	4,48	4,48	4,48	4,48	4,48	4,48	4,48	4,48	4,48
		Y [-]											0,54
		A_1 | A_4 [-]	0,66	0,58	0,58	0,58	0,61	0,61	0,64	0,58	0,61	0,51	0,62
		LL | b_1 [m]	0,30	0,30	0,37	0,30	0,30	0,30	0,31	0,30	0,30	0,30	0,92
		PPF_t | PPF_s	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,17
Requirements		A_t | A_L [cm²]	38,32	22,99	18,12	61,31	42,15	26,82	68,39	61,31	42,15	26,82	22,94
		Z_{pt} | Z_{pL} [cm³]	928,35	494,70	252,29	1311,52	947,58	601,10	1394,57	1311,52	947,58	505,65	221,07
		C601 t_w [mm]	7,05	5,30	4,42	9,45	7,48	5,73	9,45	9,45	7,48	9,45	5,30
		C603 t_w [mm]	6,54	4,96	5,64	8,12	6,76	5,41	8,12	8,12	6,76	5,41	6,99
		C604ii t_f [mm]	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
		a_{ij} [cm²]	34,98	20,99	-0,22	55,96	38,47	24,48	55,44	55,96	38,47	24,48	16,65
Status		A_w	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
		Z_p	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
	Stability	C601	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
		C603	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
		C604(i)	**Fail**	**Fail**	**Fail**	**Fail**	**Fail**	**Fail**	**Fail**	**Fail**	**Fail**	**Fail**	**Fail**
		C604(ii)	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

Nauticus Hull
2016-06-06
Ver. 17.90.85.9682

IACS Unified req. for polar class ships
Ships for Navigation in Ice, July 2013
Load carrying stringers

<Master's Thesis VE Arctic Cruise Ship>

		Id	lcs1	lcs2
		Hull area	Bow	Midbody Icebelt
		s [m]	0,43	0,43
		S [m]	2,20	0,80
		S_w [m]	2,56	2,56
		l [m]	0,45	0,45
		t_s [mm]	1,00	1,00
		a [m]	2,20	2,20
		σ_F [N/mm2]	390,00	390,00
		φ_w [°]	90,0	90,0
		Z_p [cm^3]	2609,44	2609,44
		h [mm]	860,00	860,00
		t_w [mm]	11,00	11,00
		h_w [mm]	855,00	855,00
		t_f [mm]	10,00	10,00
		b_f [mm]	100,00	100,00
		$b_{f\ out}$ [mm]	0,00	0,00
		c_2 [mm]	0,00	0,00
		End Fixity	Both ends fixed	Both ends fixed
		A_{lcs} [cm^2]	81,00	81,00
		Z_{lcs} [cm^3]	1564,70	1564,70
		w [m]	3,06	3,06
		b [m]	0,62	0,62
		AF [-]	1,00	1,00
		P_{avg} [MPa]	4,48	4,48
		PPF_s [-]	1,00	1,00
		LH_s [m]	0,41	0,41
		LL_s [m]	1,77	1,77
		η [-]	0,90	0,90
		LL_b [m]	2,20	2,20
		k_f [-]	2,00	2,00
		k_{fl} [-]	2,00	2,00
		c_1 [mm]	167,00	167,00
Req.		A_{lcs} [cm^2]	79,50	79,50
		Z_{lcs} [cm^3]	468,45	468,45
		a_0 [cm^2]	109,58	109,58
Staus		A_{lcs}	Pass	Pass
		Z_{lcs}	Pass	Pass
	Stability	C602	Pass	Pass
		C604(i)	Pass	Pass
		C604(ii	Pass	Pass

Energy Calculations for concept ship

Engines: 2 x Wärtsilä 16B50DF

2 x Wärtsilä 9L50DF

	LNG consumption						
	Load	kJ/kWh	kg/kWh		Open Water Ship	DAS	Ice Breaking Bow
				Power Delivered	2x10,5 MW	2x11,5MW	2x13,5 MW
LNG	100 %	7365	1,346435101	Power @Max BP		2x9,7MW	2x12,5MW
	75 %	7677	1,403473492				
	50 %	8300	1,517367459				
MDO	100 %		0,187				
	75 %		0,187				
	50 %		0,198				

Consumption 5000 nm

80% NCO/ 4 MW HOTEL LOAD	Metric tons	Volume
MS 5	1197,295775	1330
Open Water Ship MDO	1107,746479	1231
Open Water Ship LNG	818,0751174	1759
Ice Breaking Bow MDO	1371,126761	1523
Ice Breaking Bow LNG	1011,032864	2174
DAS MDO	1195,539906	1328
DAS LNG	882,3943662	1898

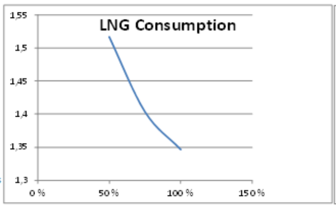
					DAS		Open Water Ship		Ice breaking bow	
Route calculation	Dist. Nautical Miles	Speed Knots	Time Hours	Time in port	LNG Cons.	MDO Cons.	LNG Cons.	MDO Consumption		
Anchora-Dutch Harbor	720	20,4	35	12	140	189	130	176	159	216
DH-Nome	790	20,4	39	12	153	207	142	192	174	236
Nome-Ulukhaktok	1557	20,4	76	12	294	398	273	370	336	455
Ulukhaktok-CB	570	20,4	28	12	112	152	105	141	128	173
CB-Resolute	477	20,4	23	12	95	129	89	120	108	146
Resolute-Bond Inlet	450	20,4	22	12	90	122	84	114	102	138
Bond Inlet - Ilulissat	566	20,4	28	12	112	151	104	140	127	172
Ilulissat - Nuuk	400	20,4	20	12	81	109	76	102	92	124
Bunkering:	5530		271		1077	1457	1003	1355	1226	1659
Nuuk - Boston	2130	20,4	104,4117647	12	400	541	371	502	457	619
Boston - New York	270	20,4	13		50	67	46	62	57	77
TOTAL	7930		660	**Weight**	1527	2065	1420	1920	1740	2356
		Total in days:	32,0	**Volume**	3284	2295	3055	2133	3742	2618
		Hours total	767,8039216	**FUEL COST**		1049510		975632		1197266
				Ticket Price		2856		2655		3258

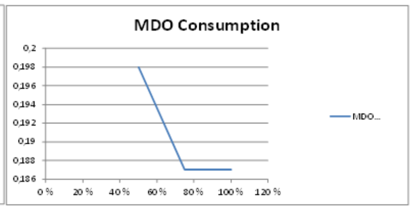
REQUIRED FUEL CAPACITY FROM ANCHORAGE TO NUUK WITH 10% RESERVE

	DAS		Open water Ship		Ice breaking bow	
	LNG Cons.	MDO Cons.	LNG Cons.	MDO Cons.	LNG Cons.	MDO Consumption
Wieght	1185	1602	1103	1491	1348	1825
VOLUME	2548,574206	1780,330996	2372,868746	1656,418033	2899,985128	2028,156922

RCCL Fuel Price Total	185 000 000	716 000 000
RCCL Fuel Used	341000	1409000
Price/Ton	542,5219941	508,1618169

Passenger ticket revenues		73,00 %	
Onboard and other revenues		27,00 %	
Total revenues		100,00 %	
Cruise operating expensese:			
Comissions, transportation and (		16,90 %	
Onboard and other		6,70 %	
Payroll and related		10,40 %	
Food		5,80 %	
Fuel		9,60 %	
Other operating		12,10 %	
Total cruise operating expense		61,40 %	
Marketing, selling and administra		13,10 %	
Depreciaton and amortization exp		10,00 %	Expenses
Impairment of Pullmantur relatec		5,00 %	
Restructuring and related impairment charger			
Operating income		10,50 %	
Other expense		-2,50 %	
Net income		8,00 %	10,41666667
Fuel price			
Fuel price	300 usd/ton		
	Net income		





ICE CONDITIONS INCLUDED

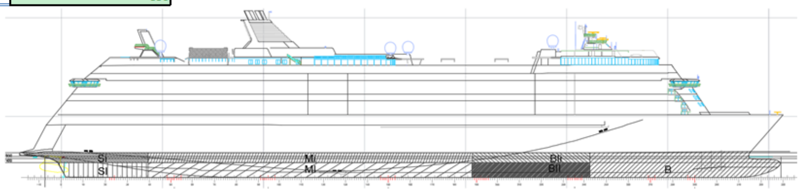
Route calculation	Dist. Nautical Miles	Speed Knots	Time Hours	Time in port	DAS LNG Cons.	DAS MDO Cons.	Ice breaking bow LNG Cons.	Ice breaking bow MDO Consumption
Anchora-Dutch Harbor	720	20,4	35	12	140	189	159	215,6569412
DH-Nome	790	20,4	39	12	153	207	174	235,6995882
Nome-Ulukhaktok	1557	20,4	76	12	294	398	336	455,3097353
Ulukhaktok-CB	570	20,4	28	12	112	152	128	172,7084118
CB-Resolute	277	20,4	14	12	58	79	66	88,81561765
Ice conditions	200	9	22	0	73	98	90	121,4888889
Resolute-Bond Inlet	450	20,4	22	12	90	122	102	138,3495882
Bond Inlet - Ilulissat	566	20,4	28	12	112	151	127	171,5631176
Ilulissat - Nuuk	400	20,4	20	12	81	109	92	124,0334118
Bunkering:	5530		283		1113	1505	1273	1723,625301
Nuuk - Boston	2130	20,4	104,4117647	12	400	541	457	619,3731176
Boston - New York	270	20,4	13		50	67	57	77,30735294
TOTAL	7930		685	**Weight**	1563	2114	1787	2420,305771
		Total in days:	33,0	**Volume**	3360	2348	3844	2689,228635
		Hours total	792,6405229	**FUEL COST**		1074048		1229902,581
				Ticket Price		2923		3347,310024
					DAS		Ice Breaking Bow	
				Effect of Ice				
				Weight	36	48	47	64
				Volume	77	54	102	71

Arctic cruise ship concept

PC 5 Whole ship, PC4 Mainframe

Webframe spacing 2562/Ordinary spacing 854

				Kaari			
Frames	115	**Painopiste Y:**	154,5720956	#164			
HULL AREA AREA	**Stern Section**		**Midship**		**Bow Section**		
POLAR CLASS	PC5						
AREA	**Si -#12 - #40**	**SI #0 - #40**	**Mi #40 - #188**	**MI #40 - #188**	**B li #188 - #242**	**Bil #188 - #242**	**B #242 - #329**
Shell Plating/Steel quality	20mm/D500	17mm/D500	16,5mm/D500	13mm/D500 & 14,5mm/D36	20mm/D500	17mm/D500	20mm/D500
Longitudinal spacing (337,5mm)-->Profile	-	-	HP320x13	HP240x12	HP430x17	HP340x14	-
Transversal spacing (427mm)-->Profile	HP430x17	HP340x14	-	-	-	-	HP430x17
Transversal intermediate frame spacing				HP200x11,5/854mm			
Sringers							T860x11/FB100x12
WEIGHT/FRAME/SIDE							
Shell Plating	434,5152	245,952	42	-326	393,5232	347,20224	1065,792
Longitudinals	2891,9856	2567,124	1031	514	1836,4416	3444,8652	
Transversals							3933,9172
Transversal intermediates				202,5			
Sringers							944,45568
Total kg	3327	2813	1073	390	2230	3792	5944
kg/m	2597	2196	838	305	1741	2960	4640
Length of the area m	50	34	125		45,5		70
Total Added weight tons/area		204,504		142,8099532		213,89732	324,817753
ICE STRENTHENING TOTAL TONS	886						



Midship	
PC4	
Mi	**MI**
19mm/D500	15,5mm/D500 & 15mm/D500
HP 400 x 16	HP300x13
-	-
	HP280x11/854mm
252,1008	-100,4304
1741,3914	826,245
	301,5
1993	1027
1556	802
125	
	294,7703747